TIDAL AND RIVER DATUMS IN THE SACRAMENTO RIVER

Fred Carl Zeile

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TIDAL AND RIVER DATUMS
IN THE SACRAMENTO RIVER

by

Fred Carl Zeile III

June 1979

Thesis Advisor: W. C. Thompson

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TIDAL AND RIVER DATUMS IN THE SACRAMENTO RIVER

by

Fred Carl Zeile III
Lieutenant, United States Navy
B.S., United States Naval Academy, 1973

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requirements for the degree of

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ABSTRACT

The problem of extending vertical tidal and river datums through the ocean/river transition zone of navigable rivers is examined through the analysis of water-level measurements from an ocean and a river station at San Francisco and Sacramento, California. Modification of the tides after passage into the transition zone was analyzed by decomposing the raw water-level data for both stations into a tidal and a non-tidal component, and comparing the tidal components for tide range ratios and time differences. It was determined that as the mean river stage increases, the range ratio and the effective tide wave speed both decrease and the symmetry of the tide wave changes. Of the six standard Pacific Coast tidal datums and five river datums defined in this study, MSL-MRL is the only common tidal/river datum that is continuous through the transition zone. The MLLW ocean charting datum and the MHW tidal waterfront property boundary datum can be carried upriver, where both effectively merge with the MRL, by a separation-addition procedure.

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I. INTRODUCTION

Vertical datum planes are used routinely for charting purposes and for the determination of waterfront property boundaries. In the fully tidal marine environment datum planes are well-defined and procedures for their determination are well-established (Marmer, 1951; Shalowitz, 1964). As these planes are extended up a navigable river they become less well-defined. Within a short distance the magnitude of the annual river stage variation becomes the same order as the range of the tide; further up the river the river stage variation may be much larger than the tidal range. Unlike the tides, which are highly repetitive and lend themselves to accurate datum determination, river levels are highly irregular in both height and duration and require a different approach for datum determination. Accordingly, datum planes that are useful in the purely tidal environment are not necessarily useful or desirable in rivers, and vice versa. The primary purpose of this study is to explore the usefulness of vertical datum planes in the transition zone between the fully tidal marine regime and the non-tidal river regime.

In order to understand what happens to conventional tidal datum planes as they are extended up a river it was necessary to determine how the tides change in response to the river stage variations. In order to accomplish this,

two water-level measuring stations on the same river system were chosen. The first was a fully tidal station, the National Ocean Survey reference tide station at the Presidio, San Francisco, California. The second was the U.S. Geological Survey gaging station at Sacramento, California in the tidal and riverine transition zone. Both stations may be considered to lie on the Sacramento River, as shown in Figure 1. A 19-year hourly water-level time-series record for the tidal epoch 1959-1977 was obtained for each station and analyzed.

The river stages at Sacramento vary from heights of above 20 feet on the water-level gage during ordinary winter and spring runoff to less than 2 feet during the dry summer season. Visual observations of the raw water-level record indicate that the tidal influence there is greatly diminished or absent during high river stages. In order to examine the character of the tides at Sacramento, the hourly raw data were decomposed into a tidal and a non-tidal component; this was done for San Francisco as well. Figures 2 and 3 show a year of raw water-level data for both stations, the tidal component extracted from the same data, and the residual water level. The range of the tide at San Francisco and Sacramento obtained from the tidal component was then compared and the time difference between the tide wave arrival at the two stations was determined, both as a function of the river stage at Sacramento.

The Sacramento water level remaining after the tidal component is removed is considered here to be representative

of the pure river regime found upriver from Sacramento at locations beyond the effective reach of the tides, whereas the raw water-level record occurring at times of successively lower river stage is considered to reasonably represent the successively increasing oceanic environment down river from Sacramento. Thus, in effect, all degrees of transition from full riverine to full tidal environment are represented in the water-level data from the two stations.

The results of this investigation are intended to provide technical guidance for the definition of datum planes in the ocean-river transition zone. Emphasis is placed on datums used for navigation and property boundary determination. It does not consider the legal aspects of property boundaries in the transition zone.

II. DATA ANALYSIS AND PROCEDURES

The raw data for this investigation were supplied by the National Ocean Survey and the U.S. Geological Survey. They consisted of a 47-year time-series of hourly water-level measurements at the Presidio, San Francisco; and a 16-year time-series of 15 minute water-level measurements and a 4-year time-series of hourly water-level measurements at the U.S. Geological Survey gaging station at Sacramento (Table 1). The San Francisco data are referenced to a staff zero which is 8.61 feet below the National Geodetic Vertical Datum (NGVD), formerly termed Sea Level Datum 1929 (SLD 1929). The Sacramento data are referenced to a staff zero at 0.00 feet NGVD (Oltmann, 1978, personal communication). For consistency in handling, all data were converted to a digital interval of one hour. The hourly data are available at the Department of Oceanography, Naval Postgraduate School on computer cards and at the Oceanographic Division of the National Ocean Survey on magnetic tape.

In order to understand the analyses performed, some knowledge of the tide and river-level characteristics at both San Francisco and Sacramento is desirable. The tide at San Francisco is a mixed tide. The range of the tide varies from about five feet during spring tides to about three feet during neap tides. The elevations of the standard tidal datum planes

and the geodetic datum plane at San Francisco for Epoch 1941-1959 are:

	Ref to Staff 0	Ref to NGVD	Ref to MLLW
MHHW	11.46 ft	2.85 ft	5.71 ft
MHW	10.86	2.25	5.11
MTL	8.86	0.25	3.11
MSL	8.80	0.19	3.05
NGVD	8.61	0.00	2.86
MLW	6.87	-1.74	1.12
MLLW	5.75	-2.86	0.00

The tide at Sacramento is also a mixed tide. Its range at spring tides varies from about three feet at low river stages to under one-tenth of a foot at high river stages. The river level, after the tides have been removed, is highly variable, with extreme values ranging from under two feet to greater than 29 feet during the period studied (1958-1977). Appendix B contains graphical printouts of these data.

In order to understand the behavior of datum planes that extend into the transition zone from both the fully tidal and fully non-tidal regimes, it was necessary to analyze the water-level data to determine the modification of the tides after passing into the riverine environment. The analyses performed of the hourly tide data at both San Francisco and Sacramento involved the following sequential steps: (1) Decomposition of the raw hourly time-series data into a tidal constituent and residual water levels in time-series form;

(2) determination of the height and time of each tide in the extracted tide curve by means of a fitted polynomial to the high and low waters; (3) comparison of the tides at each station to determine the effect of river stage on the heights and times of high and low waters; and (4) analysis of the raw time-series record at Sacramento for use in determining river datum planes. The non-tidal component at Sacramento was also analyzed and compared with the analysis in (4) above. A description of each analysis and the reason for it is given below.

A. DECOMPOSITION OF WATER-LEVEL RECORDS

In order to compare the ranges and times of the tide at the two stations, the raw data were decomposed into a tidal and a non-tidal component. The primary tidal constituent has a period of 24.8 hours; accordingly, it was decided to compute a 25-hour running mean to accomplish the primary separation. Figures 4 and 5 show an example of the raw and decomposed data at San Francisco and Sacramento, respectively, for a given five-day period. The computer program for this separation is included in Appendix A-1. This data reduction and all other computational work was accomplished on the IBM-360 computer at the W. R. Church Computer Center of the Naval Postgraduate School.

This separation procedure proved to be effective in filtering out regular variations with a period of 25 hours or less. Two distinct cyclical components remain in the Sacramento time-series. The dominant one is the irregular annual

variation in the river level due to seasonal precipitation and runoff. This variation is of a magnitude of up to 20 feet per year. The other is a harmonic component with a fortnightly period which appears to be linked to the spring-neap tide cycle. This component has a magnitude of less than 0.4 foot and was not filtered from the Sacramento residual river level. McDowell and O'Connor (1977) describe a rise in mean river level for certain rivers in India caused by an accumulation of water upriver during the spring tides, and evidently it is this phenomenon that remains in the Sacramento time-series record. Figure 6 displays this fortnightly cycle. The cycle evidently does not occur in the essentially fully marine environment at San Francisco.

It may be noted from Figure 5 that the tide waves at Sacramento are markedly asymmetrical, and in striking contrast to the tides at San Francisco for the same period shown in Figure 4. The asymmetry is attributed by McDowell and O'Connor (1977) to the fact that the tide crest moves faster than the tide trough due to increased water depth at high tide compared to that at low tide. The high tide marked A is a common tide in both figures.

In the San Francisco time series, the water-level variations that remain after the removal of the diurnal and shorter tidal components are irregular and of very low amplitude. These variations are attributed principally to meteorological effects, but must also contain very low amplitude long period tidal constituents, although none are visually evident in graphical printouts of the residuals (Appendix B).

B. HIGH WATER AND LOW WATER HEIGHTS AND TIMES

Comparison of tide heights at San Francisco and Sacramento cannot be done meaningfully in the usual way as with ocean stations. The raw water-level data at a river station contains not only the tidal component, but also the river level, which may have any arbitrary height. In order to make a comparison, the high/low water heights and times needed to be extracted from the tidal component time-series record. Although heights can be obtained accurately directly from hourly digital data by use of a computer, determination of the times of high/low waters needed to be refined in order to obtain the time to an accuracy better than the closest hour. This was accomplished by curve-fitting to the data points to obtain the times and heights to the desired precision of 0.1 hour and 0.1 foot. There were also many irregularities in the time-series record not related to the tide, especially in the Sacramento data, which made curve-fitting additionally desirable.

Curve-fitting was accomplished using a computer program written for this investigation which is best understood by reference to Figure 7. The first step was to determine an initial guess as to the time of the high or low water. The tide heights at hour times t_1 and t_2 were summed, then subtracted from the sum of the heights at times t_4 and t_5. The algebraic sign of this difference was noted and associated with the mid-point, time t_3. This procedure was indexed forward one hour and repeated, comparing heights at times t_2

and t_3 with the heights at times t_5 and t_6. The algebraic sign of the difference was associated with time t_4. This procedure was indexed an hour at a time throughout the entire record. Whenever the algebraic sign changed it was considered that a high or low water was associated with the mid-point (an hourly data point) of the last summation. This initial guess procedure gives the time of the high or low water to the closest hourly data point. Appendix A-2 contains the computer program.

Once an initial guess was made for the high/low water time, the associated water level and the two preceding and following hourly water levels were fitted to a second-order polynomial. The fitting was done in a least squares sense. Since the data points are at a regular one-hour interval, by adjusting the indexing the normal equations for the least squares fit needed to be solved only once. The heights of the five data points are simply substituted into a single equation for each of the three coefficients of the quadratic equation:

$$Y = a_0 + a_1X + a_2X^2$$

where Y is the height of the actual high/low water and X is the time of the actual high/low water. This quadratic was then differentiated, set equal to zero, and solved for X, the actual time of the high/low water. This time (to the closest 0.1 hour) was substituted into the quadratic to obtain the height of the high/low water to 0.1 foot. By way of

example, Figure 8 shows the tide heights and times derived from this procedure superimposed upon the raw data water-levels for San Francisco and Sacramento (shown in Figures 4 and 5). Table 2 compares the heights and times of the high/low waters for the San Francisco station calculated by this procedure with the heights and times derived manually by NOS from an analog tide record for the same dates. Appendix A-3 contains the normal equations for the least squares fit and also the computer program.

This objective curve-fitting technique has two potential inadequacies which are dependent upon the raw data. First, if the raw data are not sufficiently smooth, extra "high/low waters" may be extracted which represent small irregularities in the data. Each high or low series of points in the data which persists for two or more hours produces a high or low water. The second inadequacy occurs when the range of the real tide is sufficiently small, in which case the high or low waters go undetected. Both of these cases occurred in the Sacramento data, and only the first case was observed in the San Francisco data, but only very occasionally. The handling of these problems is described below.

The heights and times of the high and low waters at San Francisco and Sacramento were used to determine how the tide varies in response to the river stage at Sacramento. Other river factors, such as time-rate-of-change of mean river height, were considered to be of second-order importance and were not examined.

The range of the tide rather than the heights of the high/low waters at the two stations was chosen for comparison. The latter procedure is conventional when the stations are both fully tidal, but ceases to be satisfactory where both the height and time of the tide vary significantly in response to a varying river height. Accordingly, the range of the tide at Sacramento was divided by the range of the tide at San Francisco for the same tide, to give a range ratio, R_r.

In order to properly match up the tides at both stations, and in view of the fact that a significant number of the tides were missed and some false tides were recorded at Sacramento, the high and low waters were filtered to ensure that only genuine tides were compared. The first filtering utilized the time difference between the tide-wave passage at San Francisco and its passage at Sacramento. Tide tables and hand analysis of the water-level data indicated that this difference is about nine hours. After initially matching the tide by hand, the computer program would look at the time lag. If a tide at Sacramento occurred less than 6.5 hours after the San Francisco tide, it was assumed that a fictitious tide had been detected at Sacramento. The Sacramento tide was disregarded and the next Sacramento tide compared. If the initial time difference was greater than 14.5 hours it was assumed that a tide had been missed at Sacramento, so the San Francisco tide was disregarded and the next San Francisco tide compared. The 6.5 and 14.5 hour cutoff points were arbitrarily chosen after hand analysis of the tide records.

The second filter developed was required because of the substantial number of real and false tides with a range magnitude on the order of one-tenth of a foot or less at Sacramento. These were especially prevalent when the river level was greater than 11 feet. This second filter disregarded all tides with a range less than 0.1 foot. This difference is of the same order of magnitude as "noise" in the data.

A third filter was used to eliminate the few incorrect range comparisons that survived the first two filters. Since R_r contains an algebraic sign as well as a magnitude, if the range ratio was not a positive value, a falling tide was obviously being compared with a rising tide, or vice versa. Any R_r values that were negative were discarded.

C. RANGE RATIOS AND PHASE INTERVALS

At this point the individual R_r values retained were considered to be valid. Visual examination and hand analysis of the data determined that both R_r and the time difference, Δt, between a tide passage at San Francisco and its passage at Sacramento are dependent on the tide phase being considered. That is, the average value of R_r for the tide phase LLW-LHW is different from the average value of R_r for the phase LLW-HHW for the same river level. Also, Δt for a LLW is different from Δt for a LHW for the same river level. Accordingly, in order to determine which of eight possible tide phase intervals a measured R_r is associated with, or which of the four possible tide phases a Δt is associated with, at least five consecutive tides covering four successive phase intervals

must be detected by the computer program. This allows determination of the tide type (HHW, LHW, etc.) and the phase interval (HHW-LLW, HHW-HLW, etc.) for the river level occurring. If five consecutive tides could not be compared, tides were discarded until five consecutive tides were available. Since a phase change occurs about the time of neap tide, one or two R_r values about the time of neap tide are discarded by this procedure. This procedure is applied after all of the other filters.

Nine years of overlapping water-level data were analyzed in this manner and approximately 34% of the possible common tides at San Francisco and Sacramento survived the above filters. This amounts of 4392 data points. The average range ratios, R_r, and time differences, Δt, for all phase intervals and tide types are displayed in Figures 9-11 and Tables 3 and 4.

D. MEAN WATER-LEVEL DETERMINATION

The Sacramento time series was analyzed both by calendar years and water years (1 October-30 September). Water years are commonly used in river studies in the United States in order to avoid splitting the peak precipitation season (winter) between two years. Calendar years are commonly used in tidal studies. Five river datum planes were defined and calculated for the 19-year period 1959-1977. They include the Mean River Level (MRL), the Mean Flood Level (MFL), the Mean Low River Level (MLRL), the Mean High Monthly River Level (MHMRL), and the Mean Low Monthly River Level (MLMRL).

The MRL is the 19-year mean of the average water level for each individual calendar or water year determined from raw hourly heights, each year being given equal weight. Each year represents 8760 hourly data points (8784 during leap years). The MFL is the 19-year mean of the single extreme high raw hourly water level for each year. The MLRL is the 19-year mean of the single extreme low raw hourly water level for each year. The MHMWL is the 19-year mean of the single highest month in each year determined from raw hourly heights; the highest month is not always the same calendar month in each year. Similarly, the MLMRL is the 19-year mean of the single lowest month in each year. The latter two datums, chosen arbitrarily, were defined because they represent moderately high and low river levels lying between the MRL and the extreme high and low river datums, MFL and MLRL. It should be noted that other river datums could be defined.

To obtain an indication of the vertical variability, or stability, of these planes, a 95% confidence interval was determined for each datum using the Student-T distribution. With a confidence of 95% the true mean lies within plus or minus one interval of the calculated mean. The standard deviations for each of the datum planes were also calculated. The mean yearly and 19-year elevations of these five river datums, along with the deviation of the yearly values from the 19-year mean, are shown in Figures 12-15. The 19-year data are also given in Table 5; the tidal datums at San Francisco are included for comparison.

A separation-addition procedure for constructing river datums, which is explained in a later section, requires decomposition of the raw water-level data from Sacramento into a tidal and a non-tidal or river component, followed by computation of the mean river level derived from either the raw or the non-tidal hourly water levels. Accordingly, comparison of the mean monthly and yearly water levels at Sacramento for the period 1958-1963 was made using both the raw hourly river data and the non-tidal component. The results are given in Appendix C. The comparative values are seen to agree to within 0.02 feet in most cases. Thus, to a high degree of accuracy, those river datums that are derived from hourly readings may be obtained from either the raw data or from the non-tidal river component.

III. EFFECT OF RIVER STAGE UPON TIDE CHARACTERISTICS

It has been determined from nine years of comparative water levels (1958-1961 and 1967-1971) that, in general, as the river stage at Sacramento increases, the range ratio between Sacramento and San Francisco decreases and the time difference increases. These results are shown in Figures 9-11 and in Tables 3 and 4. It may be seen that the range ratio decreases approximately exponentially. The time difference increases approximately linearly at low river stages and tapers off at higher river stages. The reader should note that the numbers of values in Table 4 at river levels greater than or equal to ten feet are too small to give representative plots of Δt in Figure 11. River level, as used in this study, refers to the residual river level remaining after removal of the diurnal tides.

Two thousand two hundred cases of falling tide were examined. As may be seen in Figure 9 the relationship between R_r and river level is very similar for all four phase types. The mean value of R_r varied from 0.249-0.292 at river levels in the range of 2-4 feet to 0.026-0.034 at river levels of 12-14 feet. A very small number of river levels below two feet were observed and they are included in the 2-4 foot category. Two thousand one hundred ninety two cases of rising tide were examined (Figure 10). $\bar{R}_r$ varied from 0.212-0.381 at river levels of 2-4 feet to 0.026-0.034 at river levels of

12-14 feet. As stated previously, staff zero at Sacramento lies at 0.00 feet NGVD.

Two thousand two hundred cases of low waters were examined (Figure 11). The mean time difference of all low waters was found to increase from 9.14 hours at river levels in the range of 2-4 feet to 9.84 hours at river levels of 12-14 feet. Two thousand one hundred ninety two cases of high waters were examined. The mean time difference increased from 8.63 hours at river levels of 2-4 feet to 9.31 hours at river levels of 12-14 feet. The rate of increase in Δt for both low and high waters is approximately ten minutes per foot increase in river level up to a river level of 7 feet, and substantially smaller at higher levels. It may be noted that at low river stages the NOS Tide Tables indicate a difference of 7.30 hours for high tides and 9.28 hours for low tides. This is in close agreement with this study for low tides, but differs by approximately one hour for high tides.

IV. VERTICAL DATUMS

For a vertical datum plane to be useful it should possess, to as great a degree as possible, the following properties: (1) maximum vertical stability, which requires water-level measurements over as long a period as possible; (2) easy visualization, which requires a simple definition; (3) derived from continuous or suitably digitized time-series measurements at a water-level gage; (4) obtainable from simple statistical handling procedures and not from theoretical or numerical models; (5) the datum should run through the ocean/river transition zone without discontinuity; and (6) the datum plane, within the riverine environment, should lie within the normal channel of the river. The two most important of these properties, stability and continuity, are discussed below.

With regard to identifying datums that can be carried into and through the transition zone, the standard oceanic datum planes derived by NOS from the San Francisco tide measurements were considered: MHHW, MHW, MTL, MSL, MLW, and MLLW. For the river, five datums derived from river stage measurements defined previously were calculated: MFL, MHMRL, MRL, MLMRL, and MLRL. The river planes were all computed for the 19-year interval 1959-1977. Nineteen years was chosen to be consistent with a tidal epoch, although there are no variations apparent in the river levels of that periodicity.

The river planes are shown in Figures 12-15 and will be considered first in regard to vertical stability. In Table 5 their stability is given in the confidence intervals and standard deviations. Solely from the standpoint of stability, the two low water datums would be the most desirable. However, the MRL should be especially considered since it reflects all river stages with only a small degradation in vertical stability and is continuous with MSL, as is discussed below. The higher river datums are clearly least stable.

Regarding continuity, a vertical reference surface, to be useful as it passes through the ocean/river transition zone, should either be continuous or be constructed from two or more intersecting datums so as to avoid any vertical discontinuity. The MRL datum, by virtue of its similar definition and computation to MSL, is continuous through the transition zone as long as the hourly water levels are averaged over the same 19-year period, and indeed becomes MSL. The MHMRL and MLMRL datums have no counterparts among the tidal datums; however, MHMRL can be shown to intersect MHHW and MHW, and MLMRL intersects MLLW and MLW, thus satisfying the continuity requirement. These two river datums approach MSL to within 0.5 to 0.7 feet at San Francisco but never reach MSL in the purely oceanic environment. The MFL and MLRL datums also have no counterparts among the tidal datums, nor do they intersect any standard tidal planes. They appear, therefore, to have limited usefulness in the transition zone. MLRL may have some value, however, as a

navigation datum in the Sacramento River during periods of very low river level due to its minimum elevation, good stability, and ease of determination. Continuity relationships between tidal and river datums in the transition zone are summarized in Table 6.

With regard to tidal datum planes, MSL is the only plane that is continuous through the transition zone, as previously stated. It may be determined in the same manner in both the ocean and the river. All other standard tidal planes converge upon this plane as they are extended upriver.

From a practical standpoint, the tidal planes become more difficult to determine upriver as river stage variations become larger. As was indicated earlier, the range of the tides decreases with rising river level. At river levels greater than about 15 feet at Sacramento, the tides are no longer detected reliably as their range diminishes to the magnitude of the random noise in the data (0.1 foot). Thus, during periods of high runoff, individual tides from which tide-related datums might otherwise be determined are undefined. Even before that stage is reached, however, distinction between the higher and lower of the high waters, and also of the low waters, becomes uncertain so that the associated datums, i.e., MHHW and MLLW, cannot be determined. MHW and MLW might be determinable under the latter condition, however, as suggested in the following paragraph.

A possible solution to the disappearing tide problem that occurs at times of high river stage, and which also

occurs at the upriver limit of tidal influence, is the creation of datum planes (other than MRL) by a separation-addition procedure. The raw river data can be decomposed into a tidal and a non-tidal component using the simple meaning technique described earlier in this study. A mean river level can be calculated from the raw water-level record (or from the non-tidal component as discussed above). From the tides that are extracted, a mean tide range can be determined. By adding (or subtracting) one-half of the mean tide range to the mean river level, for example, an artificial mean high water (or mean low water) can be determined. In computing the mean tide range, the range of all tides including those that have disappeared into the noise background would have to be considered in order not to bias the resulting artificial MHW level (or MLW level) toward an extreme value.

A non-technical drawback to this procedure might be unwilling acceptance because of the more complex and indirect nature of the procedure. Although MHW and MLW could be computed by this method, MHHW and MLLW cannot because of the differentiation problem noted above unless values of HHW and LLW at the transition station are designated according to the tide occurrence at the ocean reference station (and tides that have disappeared are similarly accounted for).

V. SUMMARY

This study has investigated the problem of extending tidal and river datum surfaces through the ocean-river transition zone of a navigable river. It presents the results of analysis of hourly water-level measurements made over a 19-year interval (1959-1977) at two gaging stations located on the Sacramento River system, one station being the Presidio tide gage at San Francisco which represents a purely tidal regime and the other at Sacramento representing at times a tide/river regime and at other times a purely river regime.

In order to know how tidal planes may be extended up the tidal reach of the Sacramento River, a comparison was made of the tide ranges and tide times at Sacramento with San Francisco, as a function of river stage at Sacramento. To accomplish this, the water-level data at the two stations were decomposed essentially into tidal and non-tidal components by use of a 25-hour running mean of the hourly values. This procedure effectively separated out the prominent semidiurnal and diurnal tidal components and left a residual of non-tidal river stages, meteorological effects, and presumably also tidal components of long period but very low amplitude. Computer programs were developed to determine the heights and times of high/low waters to 0.1 foot/0.1 hour precision, and to filter out erroneous data. It was determined that as the river level increases due to increased

runoff, the ratio of the tide range at Sacramento to that at San Francisco decreases, and the travel time of the tide wave up the river system increases. At very high river stages, the tides at Sacramento disappear into the background river stage noise, which has a magnitude of approximately 0.1 foot. Under these conditions the regime at Sacramento is purely riverine.

The six standard tidal datum planes at San Francisco (MHHW, MHW, MTL, MSL, MLW, AND MLLW) and five river datum planes defined and considered in this study (MFL, MHMRL, MRL, MLMRL, AND MLRL) were examined for their continuity and interrelationships through the ocean-river transition zone. In addition, the stability, or vertical variability, of the river planes was determined. Regarding the latter, the low water datum planes were found to have the greatest stability.

Of the tidal datums considered, only one was found to extend continuously through the transition zone -- the MSL datum which becomes MRL upriver. This "plane" is easily visualized and calculated from digital water-level measurements made at any location in the transition zone and at the same time has relatively good stability in the riverine environment. Usage of this datum would require that MSL and MRL be calculated over the same 19-year interval to avoid a discontinuity in the plane.

Of the other tidal datums, MHW and MLW could be carried completely through the transition zone by a separation-addition procedure involving separating the tidal from the

riverine component, determining the mean range of the tidal component (taking into account all of the twice daily tides including those that have merged into the 0.1 foot background noise), and adding/subtracting half of this mean range (which might be called the mean amplitude) to/from the mean of the residual hourly values to obtain a mean high water plane or low water plane. These datums effectively merge with the MRL datum above the reach of the tides.

The MHHW and MLLW tidal datums could be extended into the pure river environment by a similar application of the separation-addition procedure, but this additionally requires identification of which of the two high waters occurring daily should be accepted as the higher high water in computing the HHW amplitude (a similar argument applies to the LLW amplitude). Such an identification procedure is necessary because when the tidal component is small during higher river stages successive values of HHW (or of LLW) are sometimes reversed from the ocean tides recorded at the reference station and at other times cannot be distinguished in recording the tide amplitudes to a precision of 0.1 foot. The logical identification procedure would be to choose those tides that are equivalent to the HHW or LLW values determined at the reference tide station (San Francisco, in the case considered here). Like the MHL/MLW tidal datums, the MHHW/MLLW tidal datums also effectively merge upriver with the MRL.

Concerning the river datums listed above, it has already been stated that MRL is continuous with MSL. The two datums

MHMRL and MLMRL have been shown to have no counterpart among the tidal datums, although they intersect the MHW and MLW planes, respectively, in the transition zone, and could therefore provide continuity with those planes through the transition zone. MFL and MLRL neither are represented in the purely tidal regime by a standard tidal plane nor intersect a standard tidal plane, hence neither can provide continuity through the river/ocean transition zone.

With regard to the Pacific Coast charting datum, MLLW, and the waterfront property boundary datum, MHW, the following summary statements can be made. MLLW can, by a procedure of separation-addition and tide identification, be extended continuously through the ocean/river transition zone where it merges upriver with the MRL datum. MHW can be similarly extended continuously through the transition zone by a separation-addition procedure where it also merges upriver with the MRL datum, or it can be carried through the transition zone to intersection with the MHMRL datum thence upriver as that datum. There appears to be no way in which MHW can be extended as a continuous surface through the transition zone so as to become a low river datum upriver.

In this study the water-level history at a single gaging station, i.e., Sacramento, was analyzed. It should be recognized that in order to carry datum surfaces through the ocean/river transition zone with a specified precision at any given location, water-level gaging stations would need to be established at suitable intervals through the transition zone.

This study represents an exploratory examination of vertical datums in the tidal reach of a navigable river. It is hoped that ideas and procedures presented here may prove useful in future tide and river level analysis and datum plane determination.

LIST OF REFERENCES

Marmer, H. A., 1951: Tidal Datum Planes, U. S. Department of Commerce, Coast and Geodetic Survey, Special Publication No. 135, 142 pp.

McDowell, D. M., and B. A. O'Connor, 1977: Hydraulic Behavior of Estuaries. John Wiley and Sons, Inc.

Oltmann, R. M., U. S. Geological Survey, Sacramento Office, personal communication, 12 December 1978.

Shalowitz, A. L., 1964: Shore and Sea Boundaries. U. S. Department of Commerce, Coast and Geodetic Survey, Publication No. 10-1 (2 vols.).

Table 1: WATER-LEVEL DATA FOR SAN FRANCISCO AND SACRAMENTO

Station	Station Number	Data Format	Time Period
San Francisco	941-4290 (NOS)	Hourly heights on magnetic tape	1941-1974
San Francisco	941-4290 (NOS)	Hourly heights on magnetic tape	1975-1977
Sacramento	11-4475 (USGS)	Hourly heights on computer cards	1958-1962
Sacramento	11-4475 (USGS)	Fifteen minute heights on magnetic tape	1963-1974
Sacramento	11-4475 (USGS)	Fifteen minute heights on magnetic tape	1975-1978

Table 2: SAN FRANCISCO HIGH AND LOW TIDE COMPARISON
All heights referenced to staff zero at
-8.61 ft NGVD

DATE 1968	NOS OBS. TIME (HOURS)	ZEILE CALC. TIME (HOURS)	TIME DIFF. (HOURS)	NOS OBS. HEIGHT (FEET)	ZEILE CALC. HEIGHT (FEET)	HEIGHT DIFF (FEET)
1 Oct	0.8	0.3	0.5	5.3	5.2	0.1
	8.5	8.4	0.1	10.6	10.5	0.1
	13.2	13.3	-0.1	8.3	8.3	0.0
	19.2	19.2	0.0	11.4	11.4	0.0
2 Oct	1.8	1.9	-0.1	5.4	5.5	-0.1
	9.2	9.4	-0.2	10.9	10.4	0.5
	14.1	13.3	0.8	8.1	7.9	0.2
	20.3	19.3	1.0	11.5	11.4	0.1
3 Oct	2.9	2.8	0.1	5.6	5.7	-0.1
	9.9	9.8	0.1	11.0	11.1	-0.1
	15.2	15.1	0.1	7.3	7.4	-0.1
	21.3	21.1	0.2	11.3	11.3	0.0
4 Oct	3.2	3.4	-0.2	5.7	5.8	-0.1
	10.1	10.2	-0.1	11.2	11.1	0.1
	15.8	15.8	0.0	6.7	6.8	-0.1
	22.3	22.2	0.1	11.0	11.0	0.0
5 Oct	4.1	3.9	0.2	6.2	6.2	0.0
	10.9	10.8	0.1	11.3	11.2	0.1
	16.5	16.6	-0.1	6.4	6.4	0.0

Table 3: RANGE RATIOS BETWEEN SAN FRANCISCO AND SACRAMENTO

$R_r = R_{Sacramento}/R_{San\ Francisco}$

Phase Interval	Mean River Height	Range Ratio	Data
HLW-LHW	2- 4 feet	0.311	193
	4- 6	0.209	261
	6- 8	0.128	43
	8-10	0.091	22
	10-12	0.052	2
HLW-HHW	2- 4	0.238	51
	4- 6	0.161	82
	6- 8	0.105	33
	8-10	0.062	15
	10-12	0.033	12
	12-14	0.026	1
LLW-LHW	2- 4	0.381	383
	4- 6	0.283	609
	6- 8	0.202	115
	8-10	0.106	32
	10-12	0.044	7
	12-14	0.025	1
LLW-HHW	2- 4	0.212	145
	4- 6	0.125	129
	6- 8	0.072	32
	8-10	0.049	19
	10-12	0.032	5
LHW-HLW	2- 4	0.264	125
	4- 6	0.201	142
	6- 8	0.118	48
	8-10	0.084	22
	10-12	0.043	6
	12-14	0.030	2
LHW-LLW	2- 4	0.260	310
	4- 6	0.169	528
	6- 8	0.094	101
	8-10	0.068	31
	10-12	0.034	5

Table 3 (Continued)

Phase Interval	Mean River Height	Range Ratio	Data
HHW-HLW	2- 4	0.249	198
	4- 6	0.173	246
	6- 8	0.096	35
	8-10	0.064	18
	10-12	0.026	1
HHW-LLW	2- 4	0.292	96
	4- 6	0.170	168
	6- 8	0.160	70
	8-10	0.077	35
	10-12	0.053	11
	12-14	0.034	2

Table 4: TIME DIFFERENCE BETWEEN TIDE PASSAGE AT SAN FRANCISCO AND SACRAMENTO

$\Delta t = t_{\text{San Francisco}} - t_{\text{Sacramento}}$

Tide Type	Mean River Height	Time Difference	Data
LHW	2- 4 feet	8.49 hours	576
	4- 6	8.69	870
	6- 8	9.26	158
	8-10	9.34	54
	10-12	9.19	9
	12-14	11.1	1
HHW	2- 4	8.77	196
	4- 6	9.08	211
	6- 8	9.34	65
	8-10	9.53	34
	10-12	9.37	17
	12-14	9.83	1
HLW	2- 4	9.36	323
	4- 6	9.66	388
	6- 8	10.01	83
	8-10	10.07	40
	10-12	10.12	7
	12-14	10.45	2
LLW	2- 4	8.97	406
	4- 6	8.93	696
	6- 8	9.31	171
	8-10	9.72	66
	10-12	9.72	16
	12-14	9.78	2

Table 5: 19-YEAR DATUM PLANE ELEVATIONS AT SAN FRANCISCO AND SACRAMENTO
All datum heights are referenced to NGVD

Datum Plane	Sample Mean Height	95% Confidence Half-width	Standard Deviation
SACRAMENTO (1959-1977)			
	Water Years		
MFL	21.11 feet	2.26 feet	4.70 feet
MHMRL	14.86	2.79	5.79
MRL	7.39	1.26	2.62
MLMRL	3.86	0.42	0.88
MLRL	2.39	0.41	0.85
	Calendar Years		
MFL	22.78	2.82	5.32
MHMRL	14.96	2.70	5.61
MRL	7.50	1.07	2.22
MLMRL	3.99	0.53	1.08
MLRL	2.69	0.50	1.03
SAN FRANCISCO (1941-1959 Epoch)			
MHHW	2.85		
MHW	2.25		
MTL	0.25		
MSL	0.19		
MLW	-1.74		
MLLW	-2.86		

Table 6: DATUM PLANE RELATIONSHIPS

River Datums	Ocean Datums					
	MHHW	MHW	MTL	MSL	MLW	MLLW
MFL	0	0	0	0	0	0
MHMRL	X	X	0	0	0	0
MRL	0	0	0	X,C	0	0
MLMRL	0	0	0	0	X	X
MLRL	0	0	0	0	0	0

0 = Planes do not intersect in the transition zone

X = Planes intersect in the transition zone

C = Planes are continuous through the transition zone

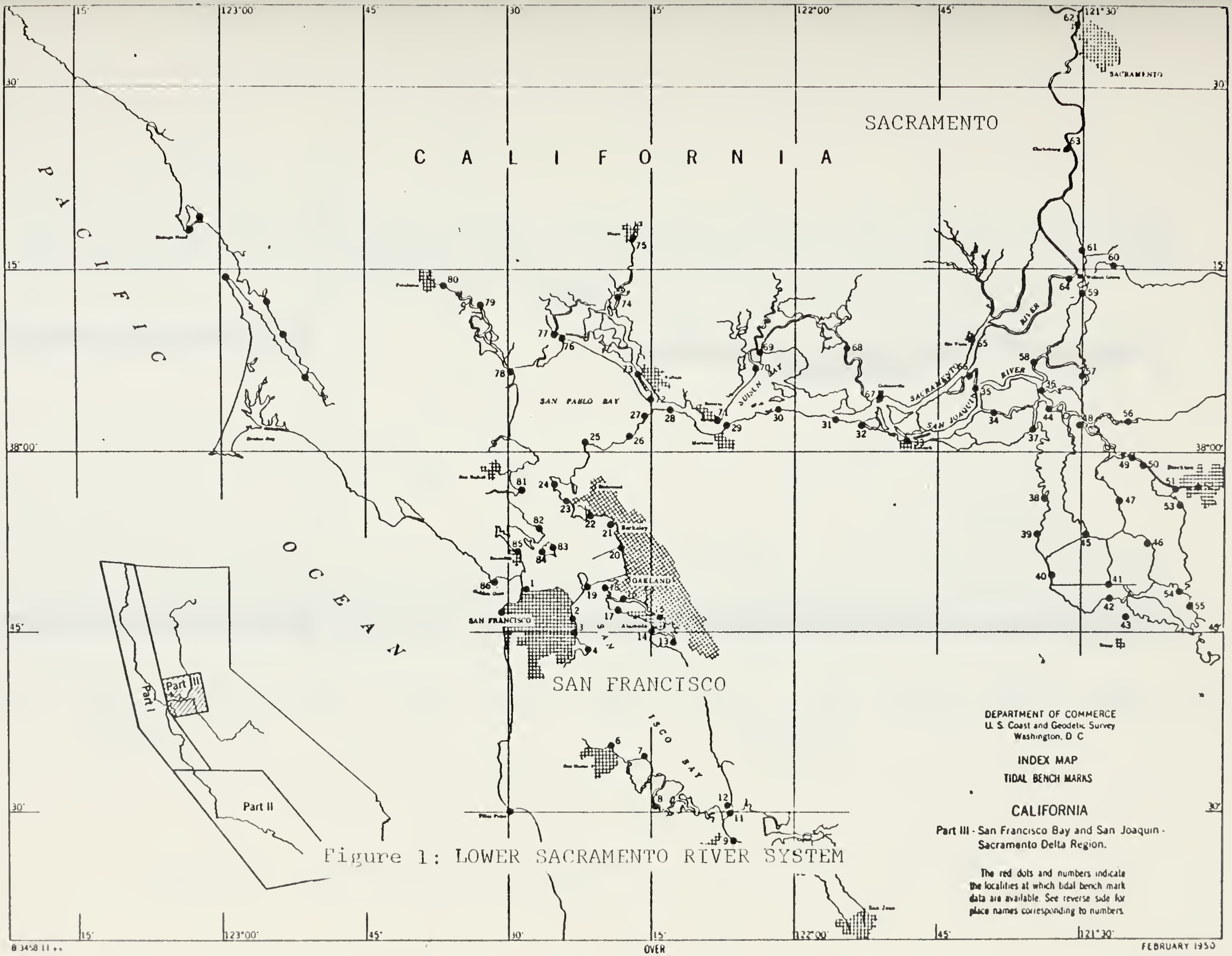


Figure 1: LOWER SACRAMENTO RIVER SYSTEM

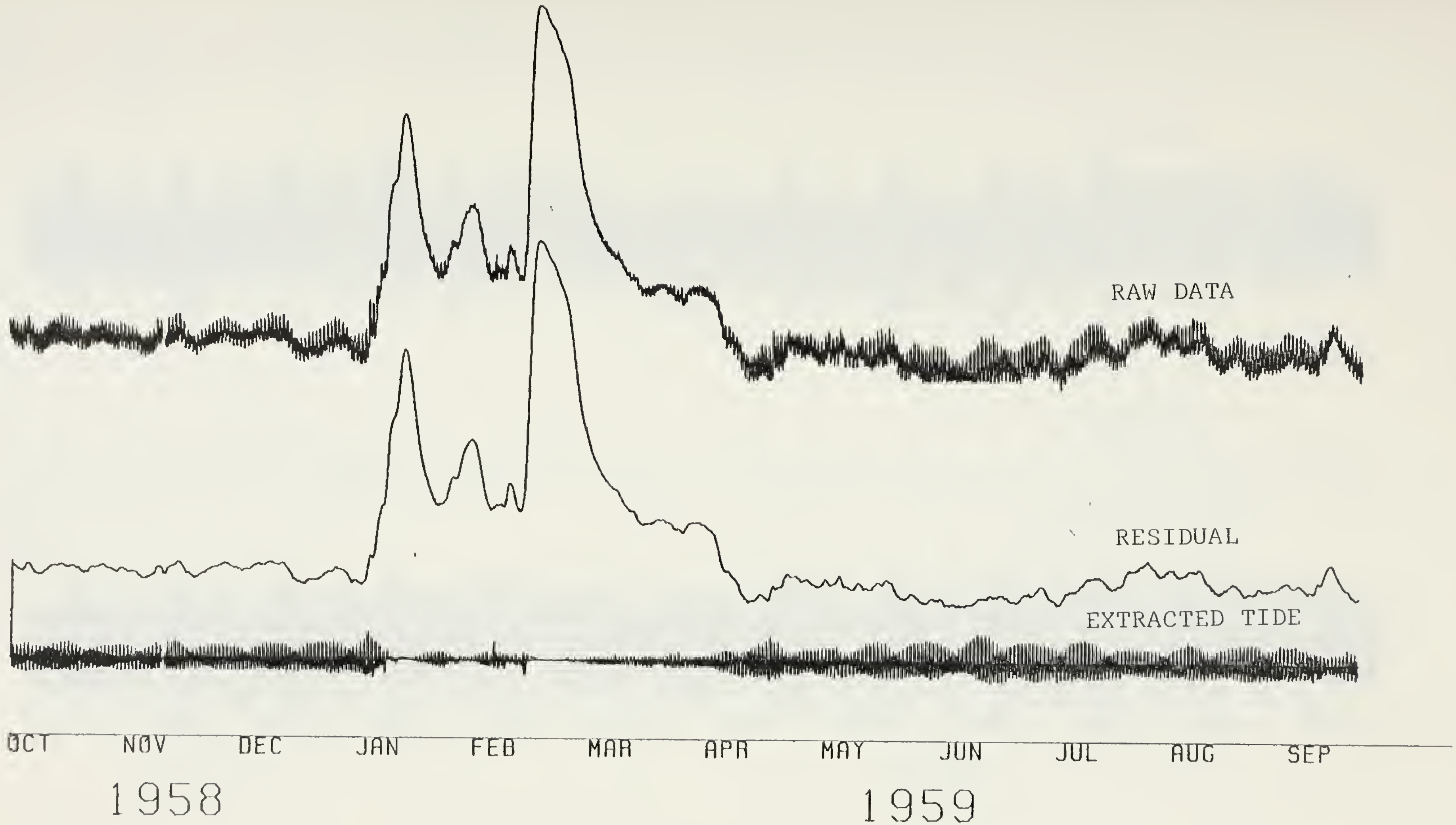


Figure 2: WATER-LEVEL AT SACRAMENTO FOR WATER YEAR 1958-1959

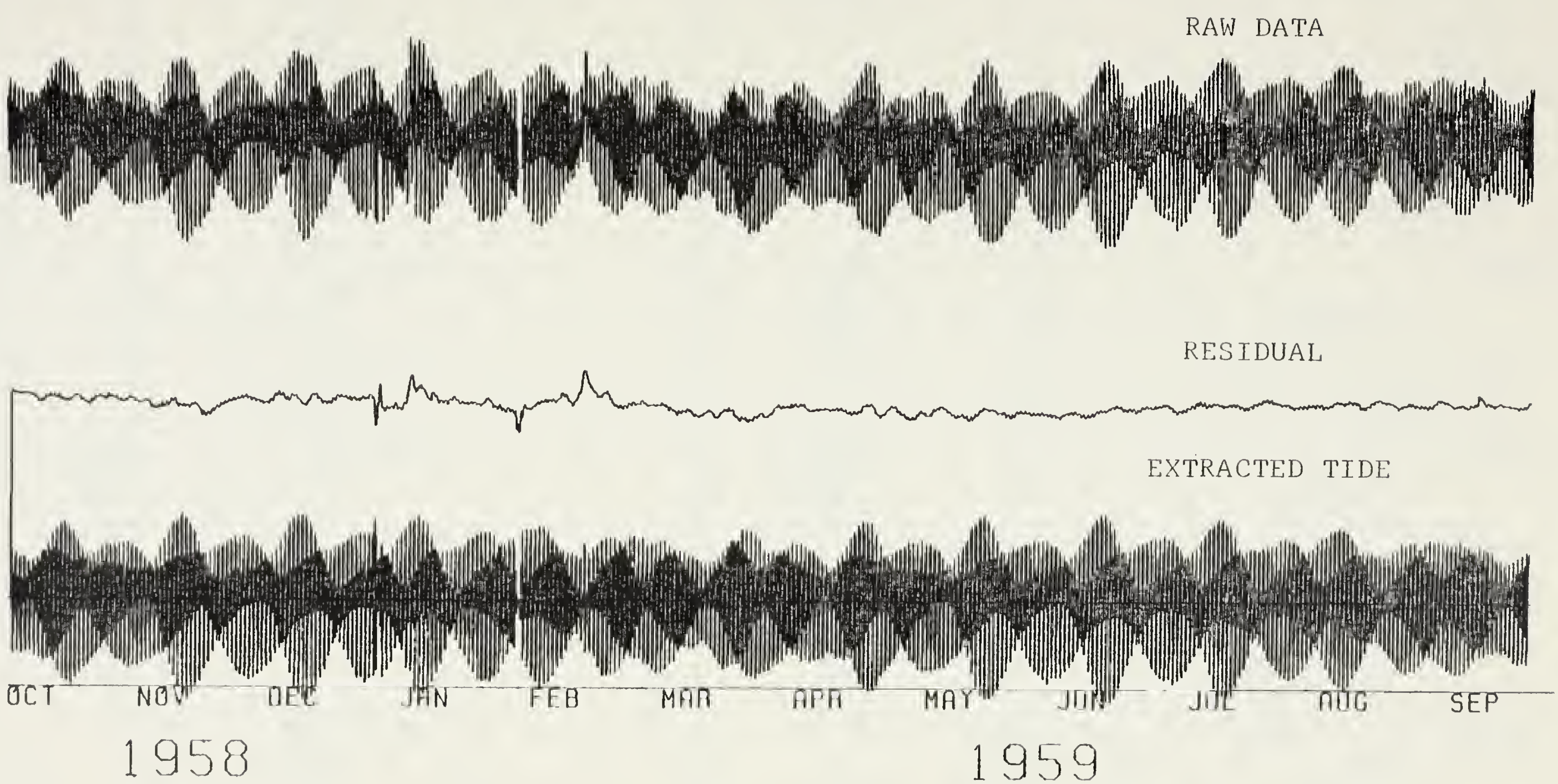


Figure 3: WATER-LEVEL AT SAN FRANCISCO FOR WATER YEAR 1958-1959

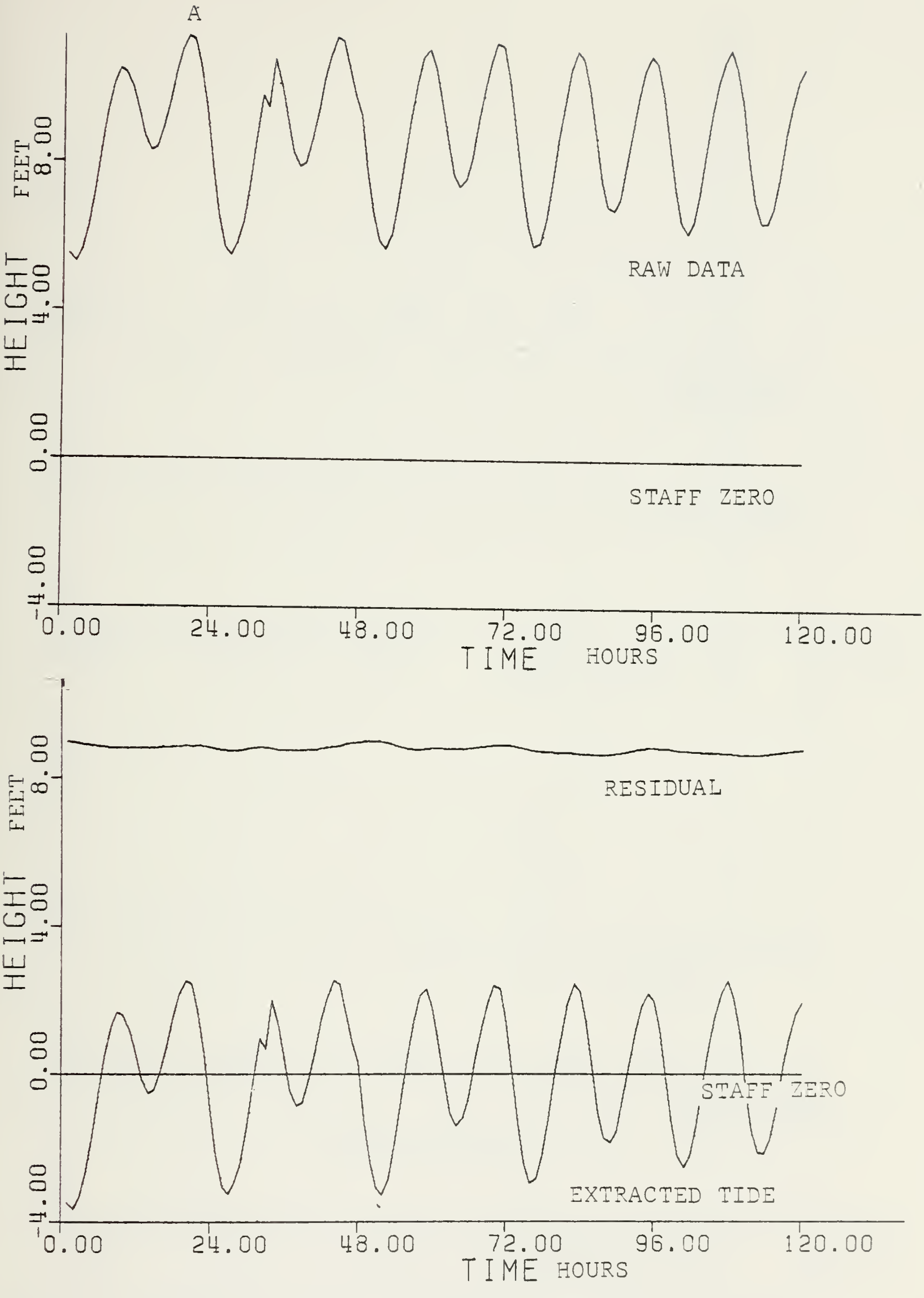
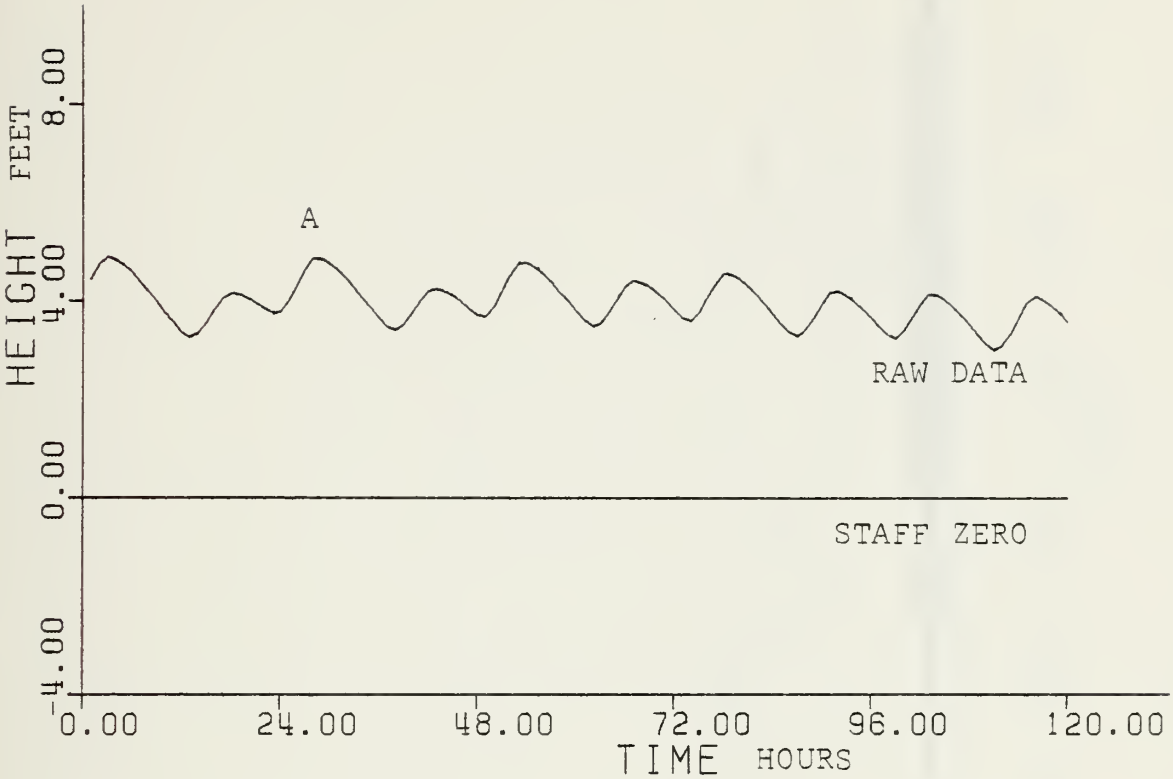


Figure 4: SAN FRANCISCO DATA DECOMPOSITION (1-5 OCT 1968)



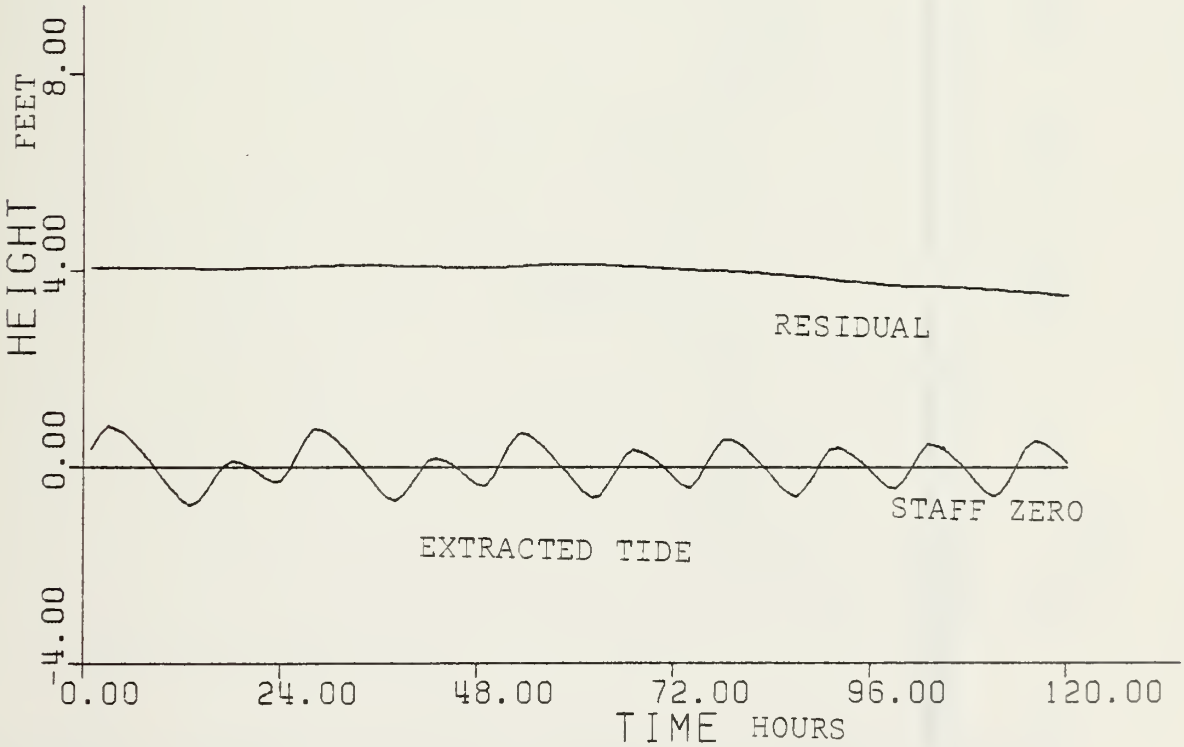


Figure 5: SACRAMENTO DATA DECOMPOSITION (1-5 OCT 1968)

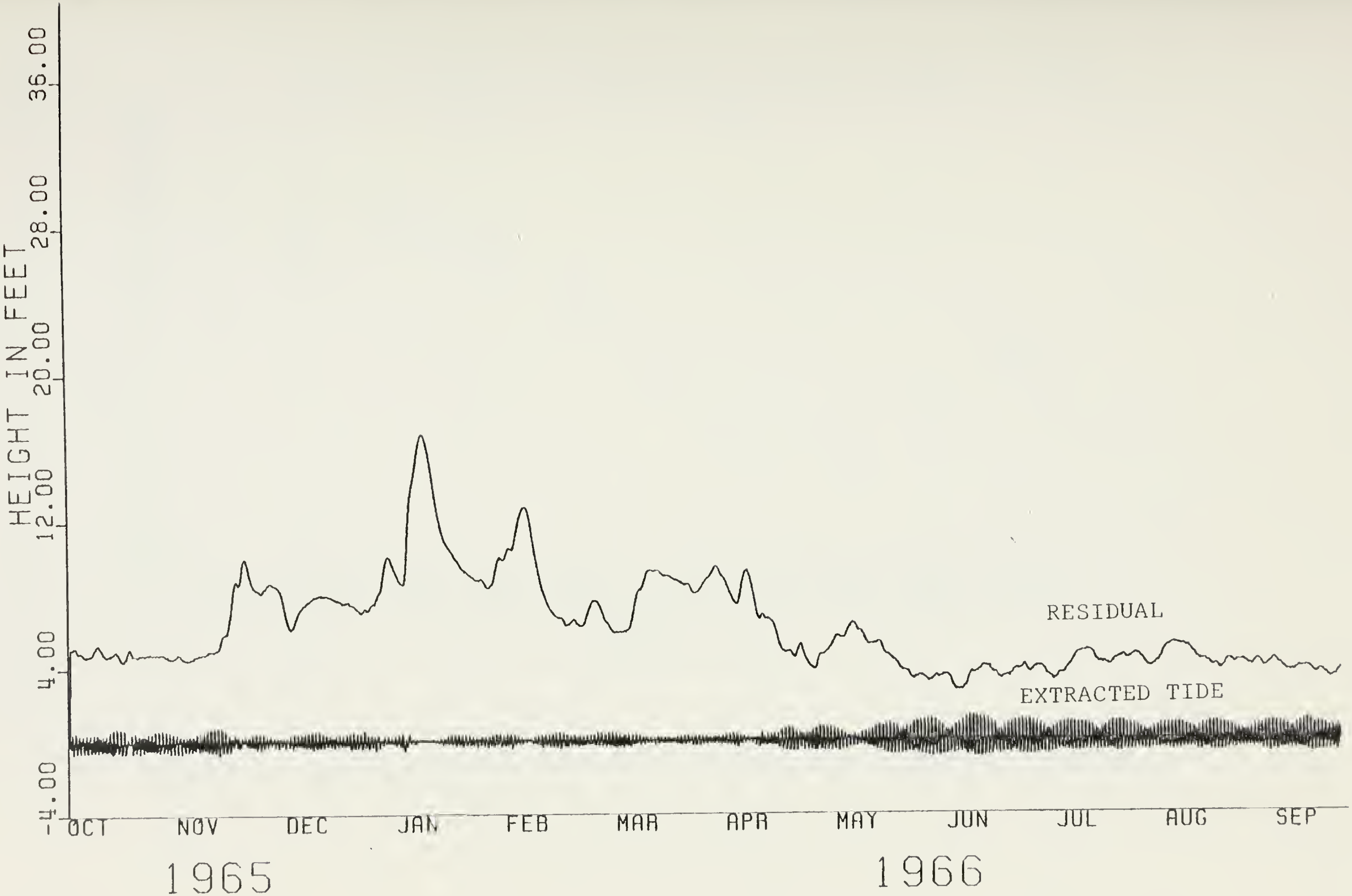


Figure 6: SACRAMENTO DATA SHOWING FORTNIGHTLY VARIATION IN RIVER HEIGHT

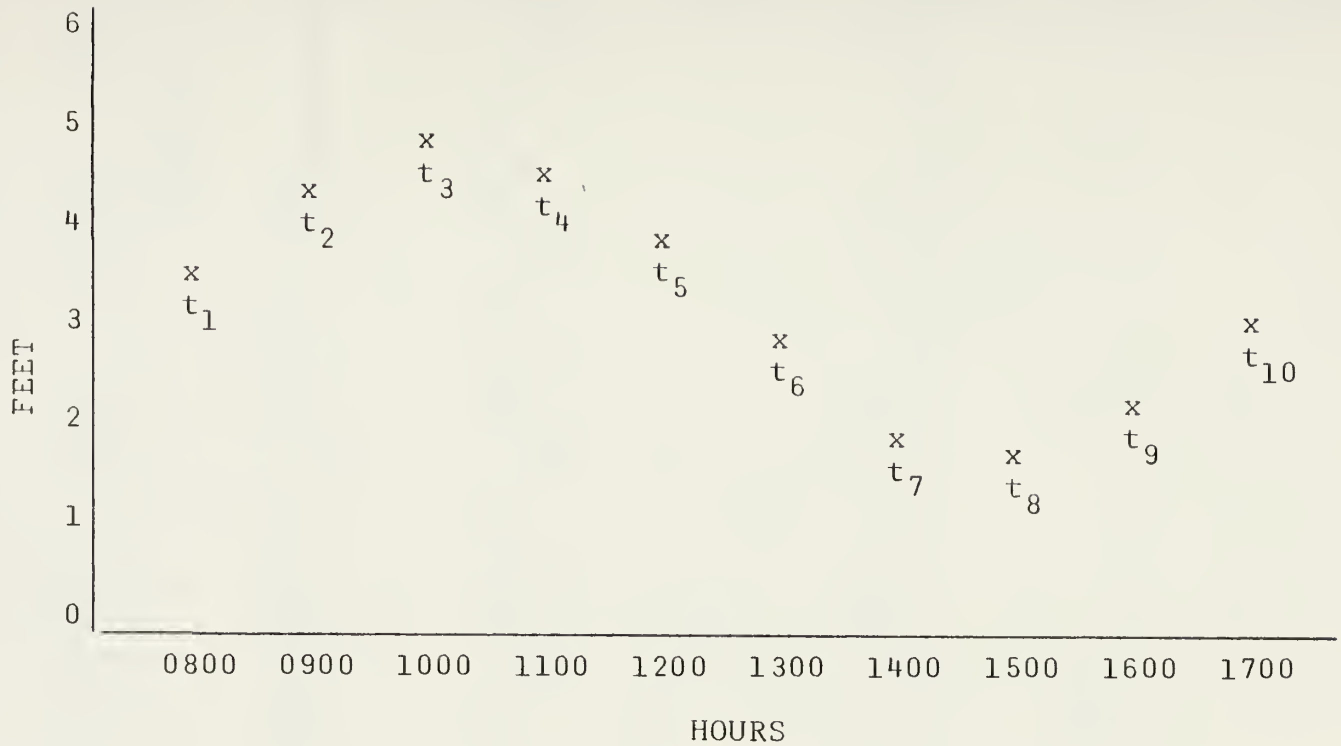
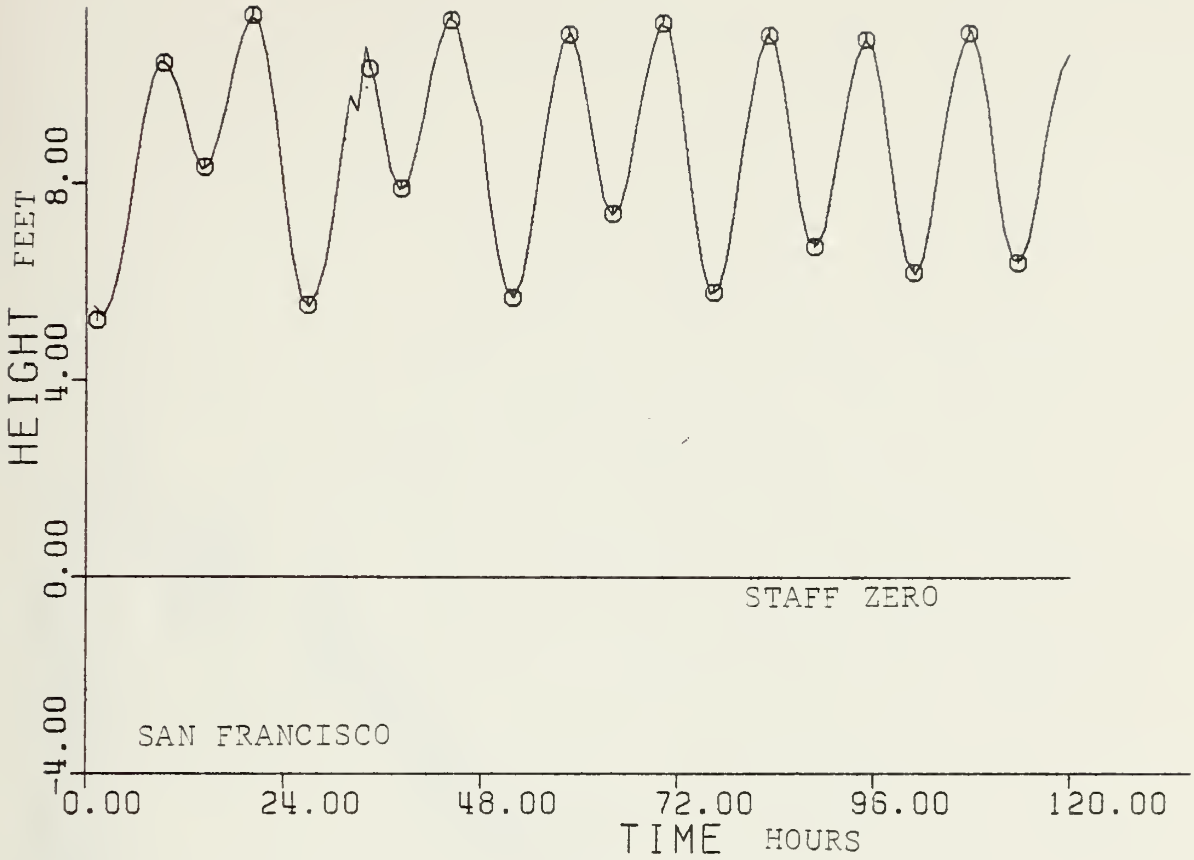


Figure 7: GRAPHICAL PRESENTATION OF INITIAL GUESS COMPUTER PROGRAM



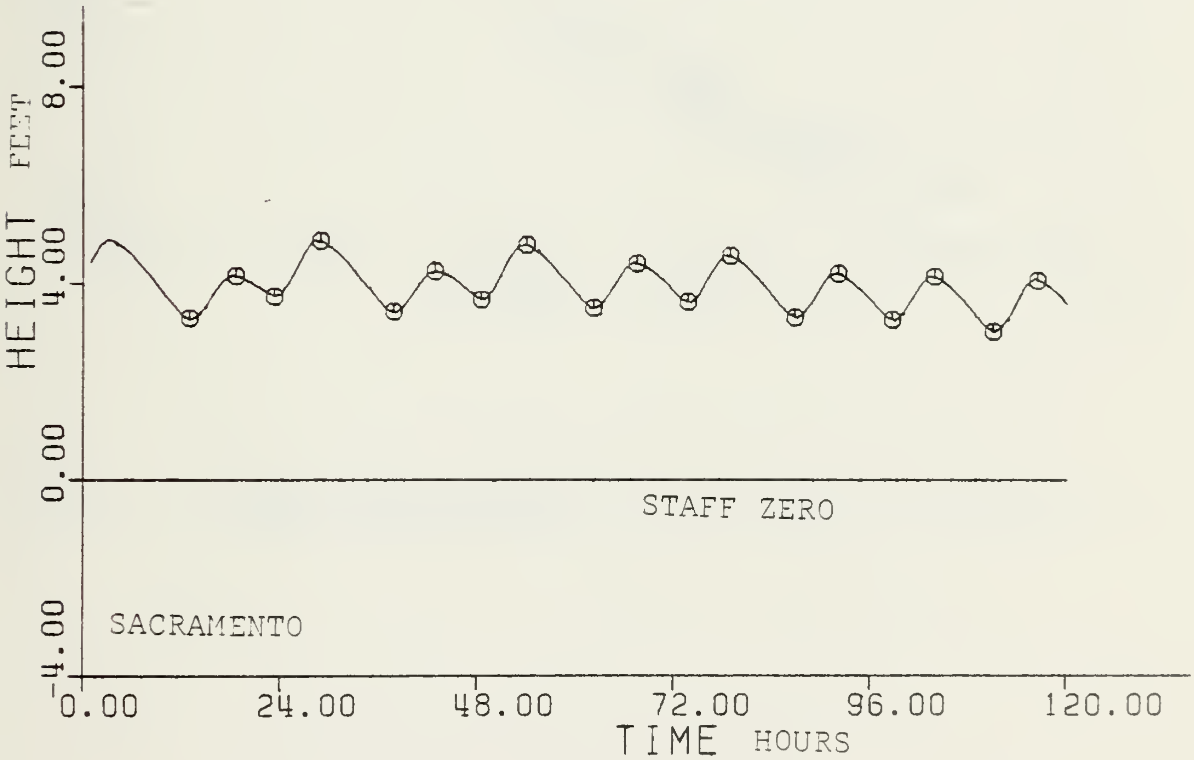


Figure 8: COMPUTER CALCULATED HIGH/LOW WATERS SUPERIMPOSED ON RAW DATA CURVES (1-5 OCT 1968)

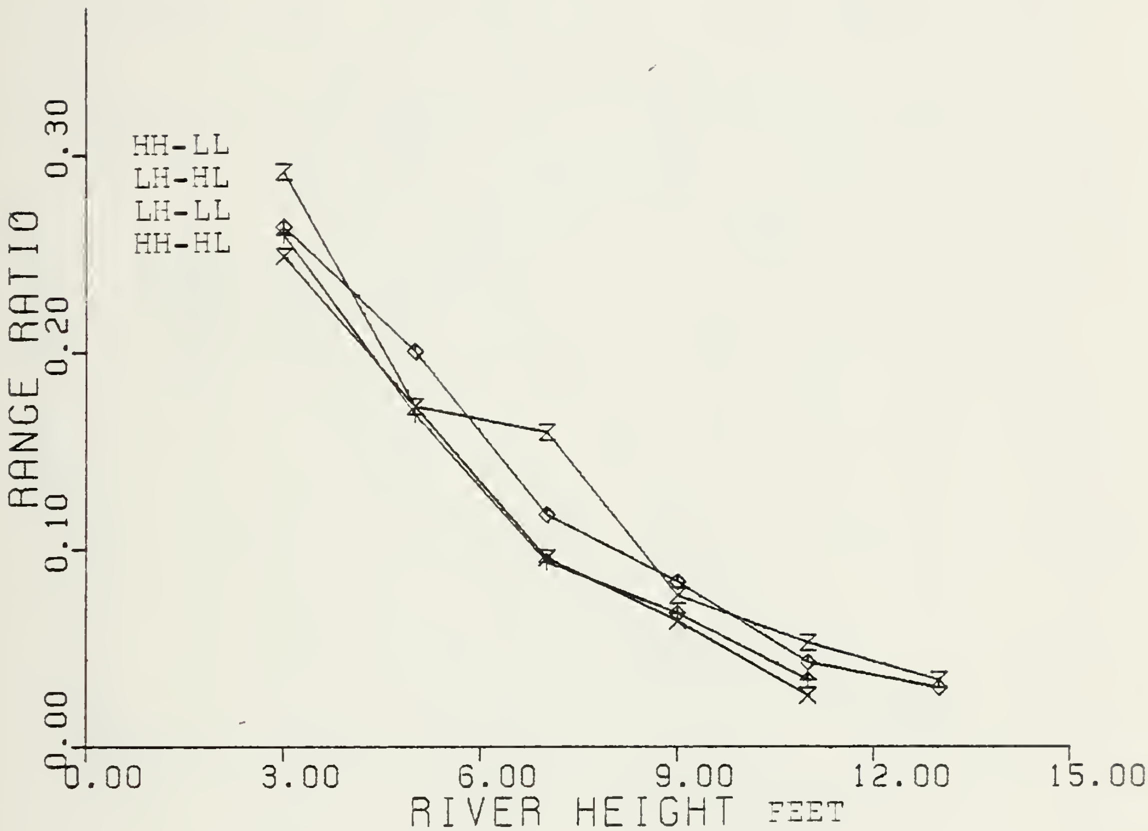


Figure 9: RANGE RATIO VERSUS RIVER HEIGHT FOR FALLING TIDE (See Table 3)

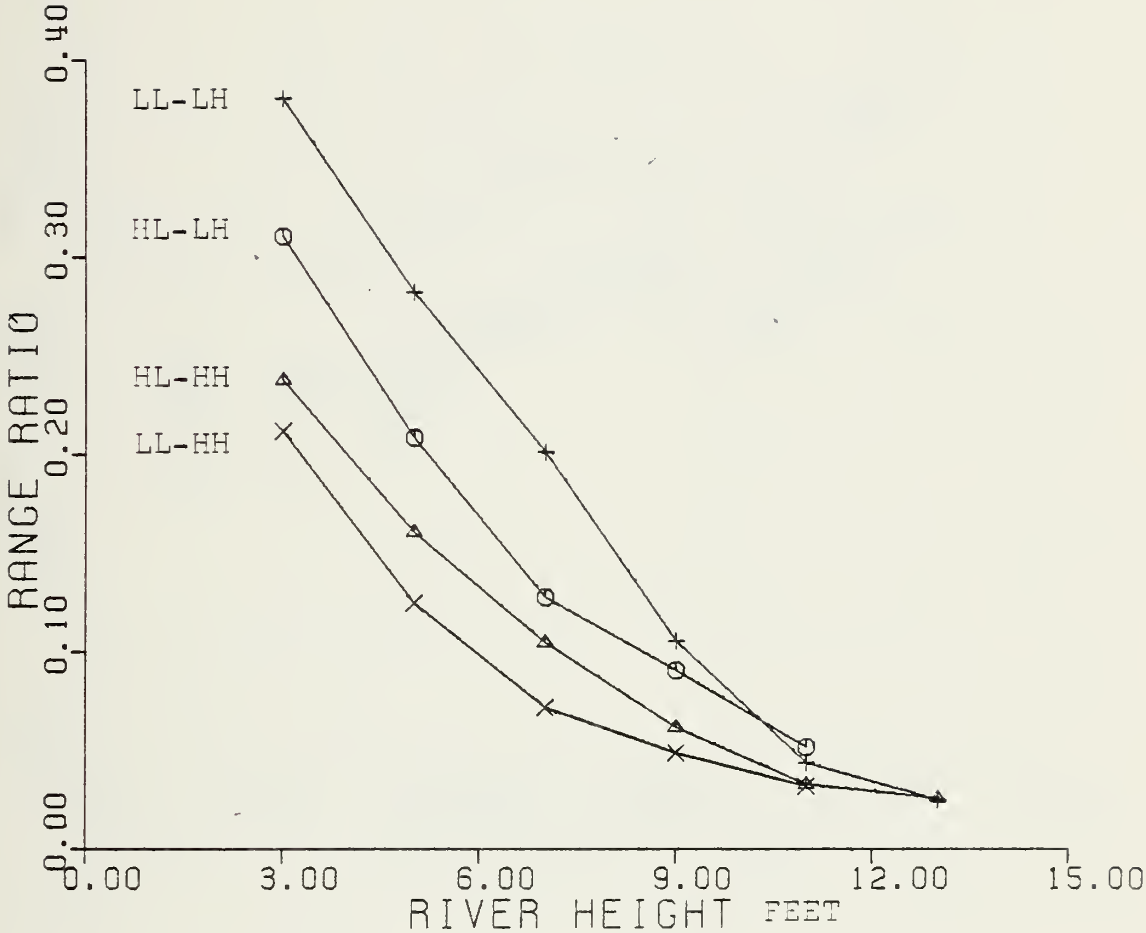


Figure 10: RANGE RATIO VERSUS RIVER HEIGHT FOR RISING TIDE (See Table 3)

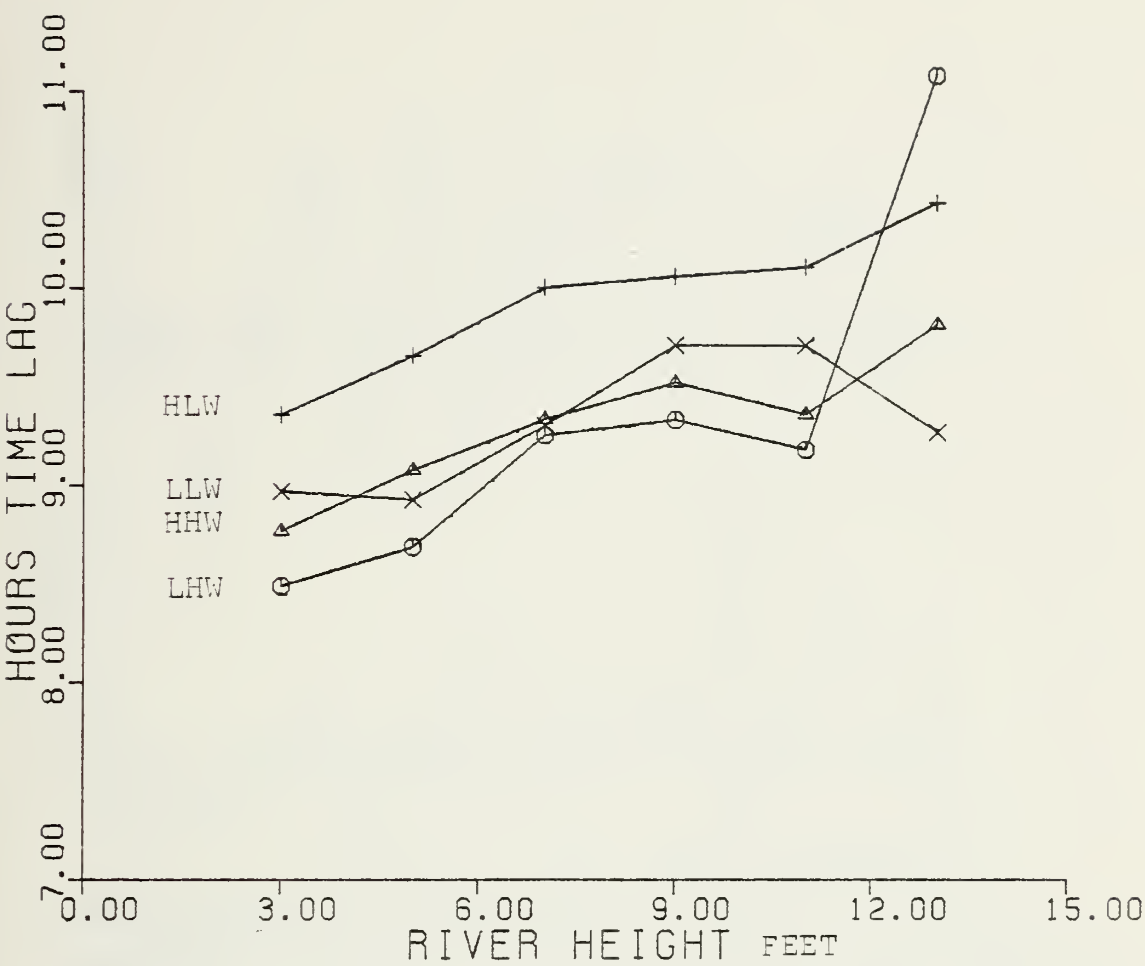


Figure 11: TIME DIFFERENCES VERSUS RIVER HEIGHT (See Table 4)

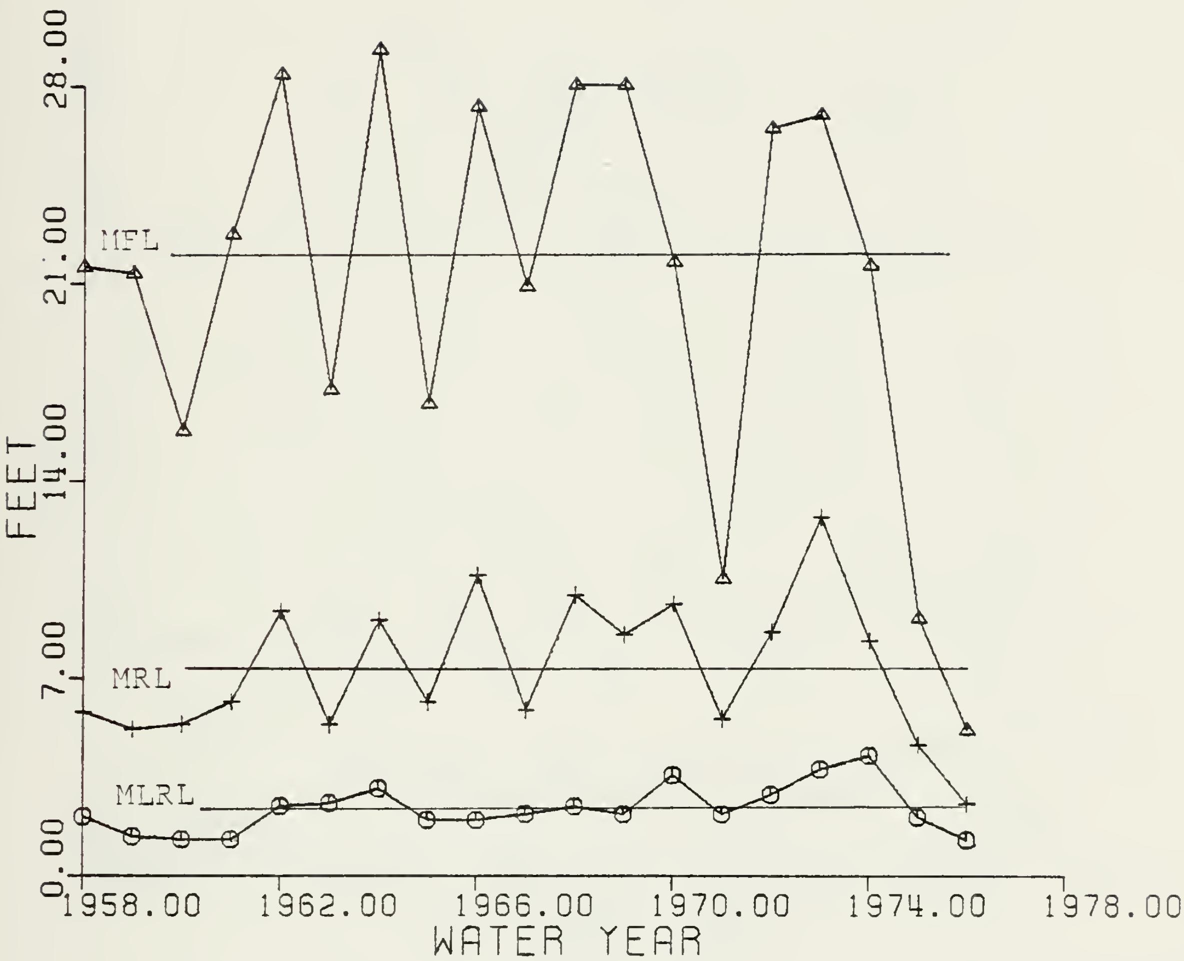


Figure 12: MRL, MLRL, MFL FOR SACRAMENTO BY WATER YEARS

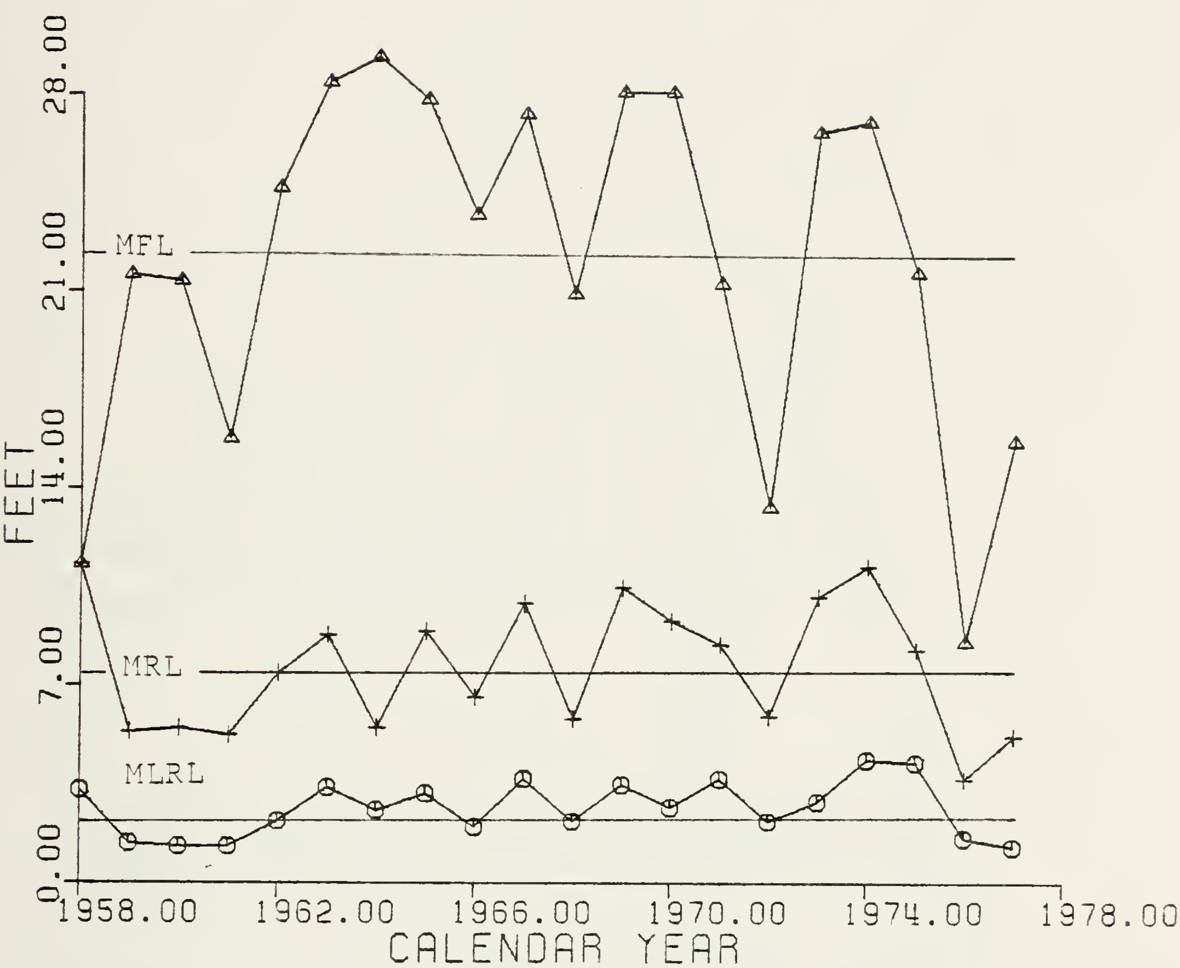


Figure 13: MRL, MLRL, MFL FOR SACRAMENTO BY CALENDAR YEARS

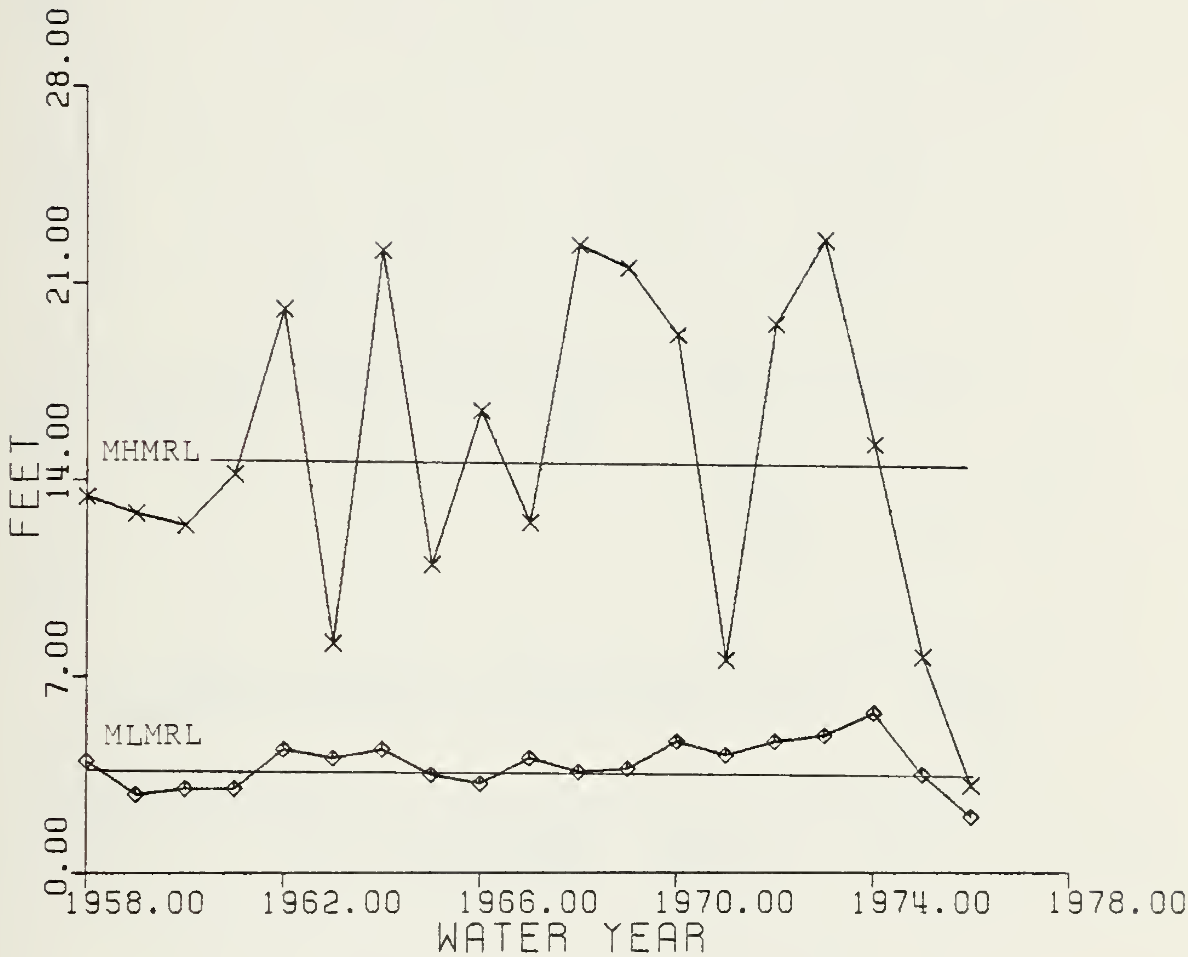


Figure 14: MHMRL, MLMRL FOR SACRAMENTO BY WATER YEARS

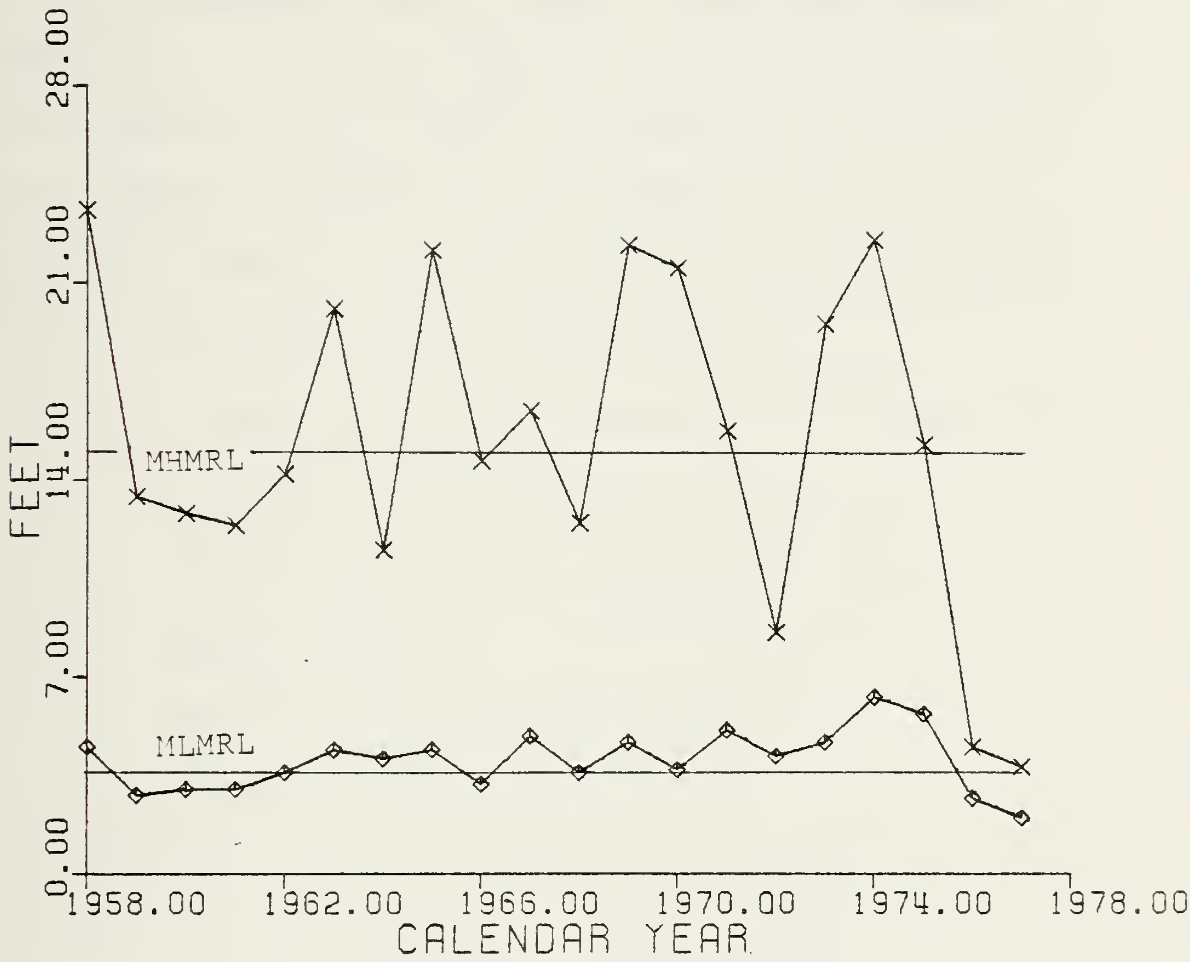


Figure 15: MHMRL, MLMRL FOR SACRAMENTO BY CALENDAR YEARS

Appendix A: COMPUTER PROGRAMS

Appendix A-1

This computer coding is used to separate the raw water-level data into a tidal and a non-tidal component by computation of a 25-hour running mean of the hourly water levels. "Heights" are the individual raw data points. "Amean" is the 25-hour running mean value, and "Tide" is the extracted tidal component.

RAW WATER-LEVEL DECOMPOSITION PROGRAM

```
      HH=Height(1)+Height(2)+...+Height(25)
      Do 30  J=1,  K
      Amean(J)=HH/25.
      Tide(J) =Height(J+12)- Amean(J)
      HH=HH - Height(J)+Height(J+25)
   30 Continue
```

Appendix A-2

This computer coding is used to determine when a high or low point in the data has been passed. It uses a finite difference scheme to give a rough first derivative of the curve containing the hourly data points. In this program "Tide" is the extracted tidal component of the raw water-level data. "IC" and "ID" are indicators which determine the change in slope of the curve.

HIGH/LOW WATER INITIAL GUESS PROGRAM

```
    J = 0
    ID = +1
    Do  60  K = 1,  LK
    A = Tide(K) + Tide(K+1) - Tide(K+3) - Tide(K+4)
    If (A)  1, 2, 3
 1  IC = -1
    Go to 4
 3  IC = +1
 4  Continue
    If (ID + IC)  60, 5, 60
 2  IC = -IC
 5  ID = IC
        +
        +
        +
60  Continue
```

Appendix A-3

The five hourly data points surrounding an initial guess at a high or low water level were fitted to a quadratic equation of the form:

$$y = a_0 + a_1 x + a_2 x^2$$

where y is water level and x is time. The normal equations for a second-order least-squares fit are:

$$a_0 N + a_1 \sum_{i=1}^{N} x_i + a_2 \sum_{i=1}^{N} x_i^2 = \sum_{i=1}^{N} y_i$$

$$a_0 \sum_{i=1}^{N} x_i + a_1 \sum_{i=1}^{N} x_i^2 + a_2 \sum_{i=1}^{N} x_i^3 = \sum_{i=1}^{N} x_i y_i$$

$$a_0 \sum_{i=1}^{N} x_i^2 + a_1 \sum_{i=1}^{N} x_i^3 + a_2 \sum_{i=1}^{N} x_i^4 = \sum_{i=1}^{N} x_i^2 y_i$$

For this investigation N always equals 5, and by adjusting the indexing the times can always be 1, 2, 3, 4, and 5. In this case the normal equations reduce to:

$$5a_0 + 15a_1 + 55a_2 = \sum_{i=1}^{5} y_i$$

$$15a_0 + 55a_1 + 225a_2 = \sum_{i=1}^{5} x_i y_i$$

$$55a_0 + 225a_1 + 979a_2 = \sum_{i=1}^{5} x_i^2 y_i$$

Solving these equations simultaneously gives the following equations for the coefficients of the quadratic in which the water-levels are the only unknowns:

$$a_2 = (-3/11)\{[(\sum_{i=1}^{5} x_i^2 y_i - 11 \sum_{i=1}^{5} y_i)/6]$$

$$- [(15 \sum_{i=1}^{5} x_i^2 y_i - 55 \sum_{i=1}^{5} x_i y_i)/55]\}$$

$$a_1 = [(\sum_{i=1}^{5} x_i^2 y_i - 11 \sum_{i=1}^{5} y_i)/60] - (374a_2/60)$$

$$a_0 = (\sum_{i=1}^{5} y_i/5) - 3a_1 - 11a_2$$

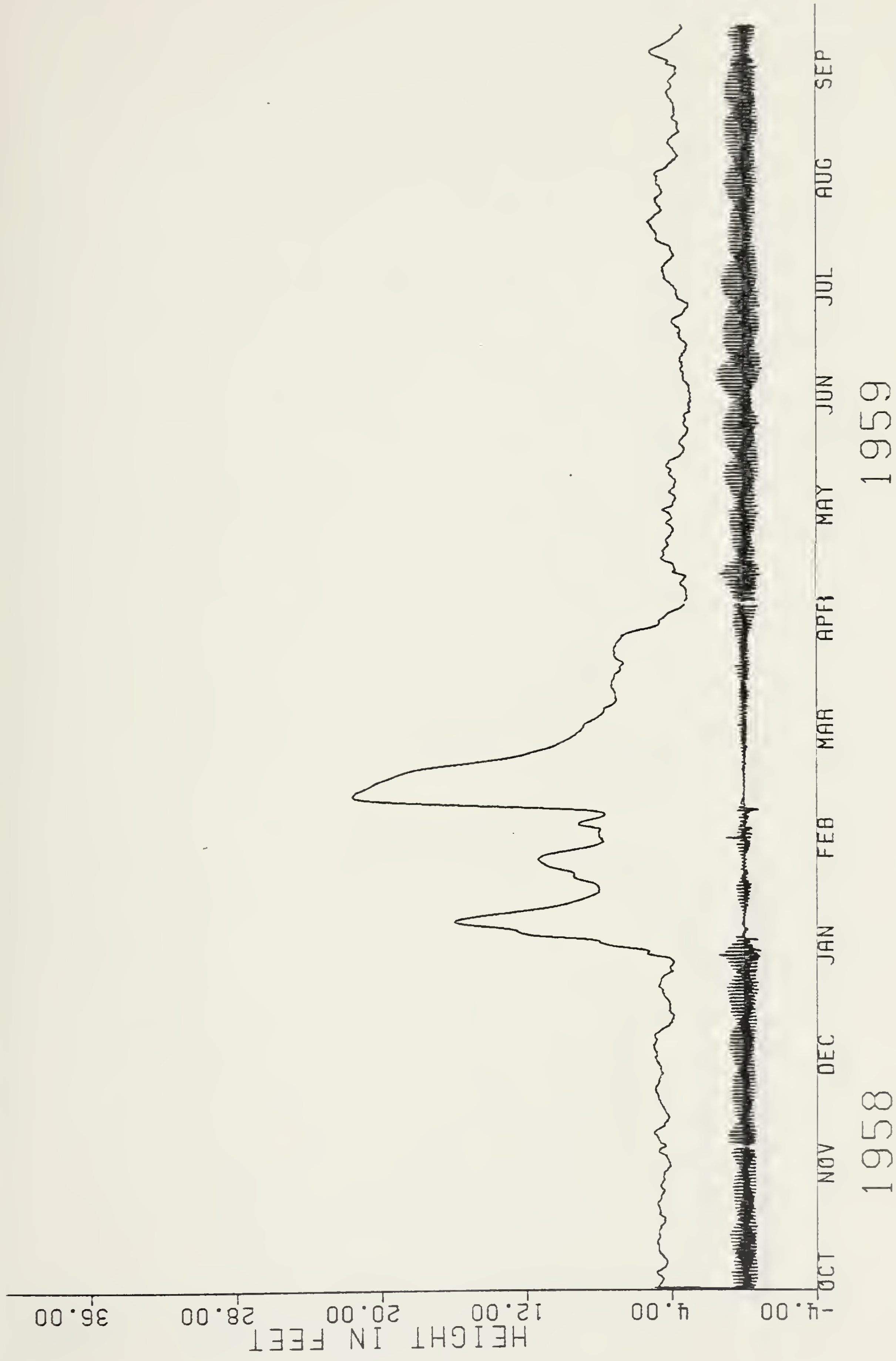
"Tide" refers to hourly water-levels associated with the extracted tidal component, i.e., the tidal component extracted by use of the 25 hour running mean (given in Appendix A-1) applied to either ocean or river water-level data. "a_2", "a_1", and "a_0" are the coefficients of the quadratic being fitted. "Time" is the differential of the quadratic set equal to zero, therefore the time of high/low water. "Height" is the high/low water height.

CURVE-FITTING PROGRAM

```
J = J + 1

FZ = Tide(K) + 4.*Tide(K+1) + 9.*Tide(K+2) + 16.*Tide(K+3)

     +25*Tide(K+4)

FC = Tide(K) + Tide(K+1) + Tide(K+2) + Tide(K+3) + Tide(K+4)

FL = Tide(K) +2.*Tide(K+1) +3.*Tide(K+2) +4.*Tide(K+3)

     +5.*Tide(K+4)

A2 = -(3./11.)*(((FZ-11.*FC)/6.)-( 15.*FZ-55.*FL)/35.)

A1 = (FZ-11,*FC)/60.-((374./60.)*a2)

A0 = FC/5.-3.*A1-11*A2

Time(J) = -A1/(2.*A2)

Height(J) = A0 + Time(J_*A1 + Time(J) **2*A2

Time(J) = Time(J) + Float(K)
```

Appendix B: GRAPHS OF ANNUAL WATER-LEVELS AT SACRAMENTO AND SAN FRANCISCO

This Appendix consists of graphical printouts of hourly water-levels for the 19 water years (1959-1977) studied at Sacramento, followed by four years of San Francisco data (1959-1962) for comparison. Both tidal and non-tidal components are shown.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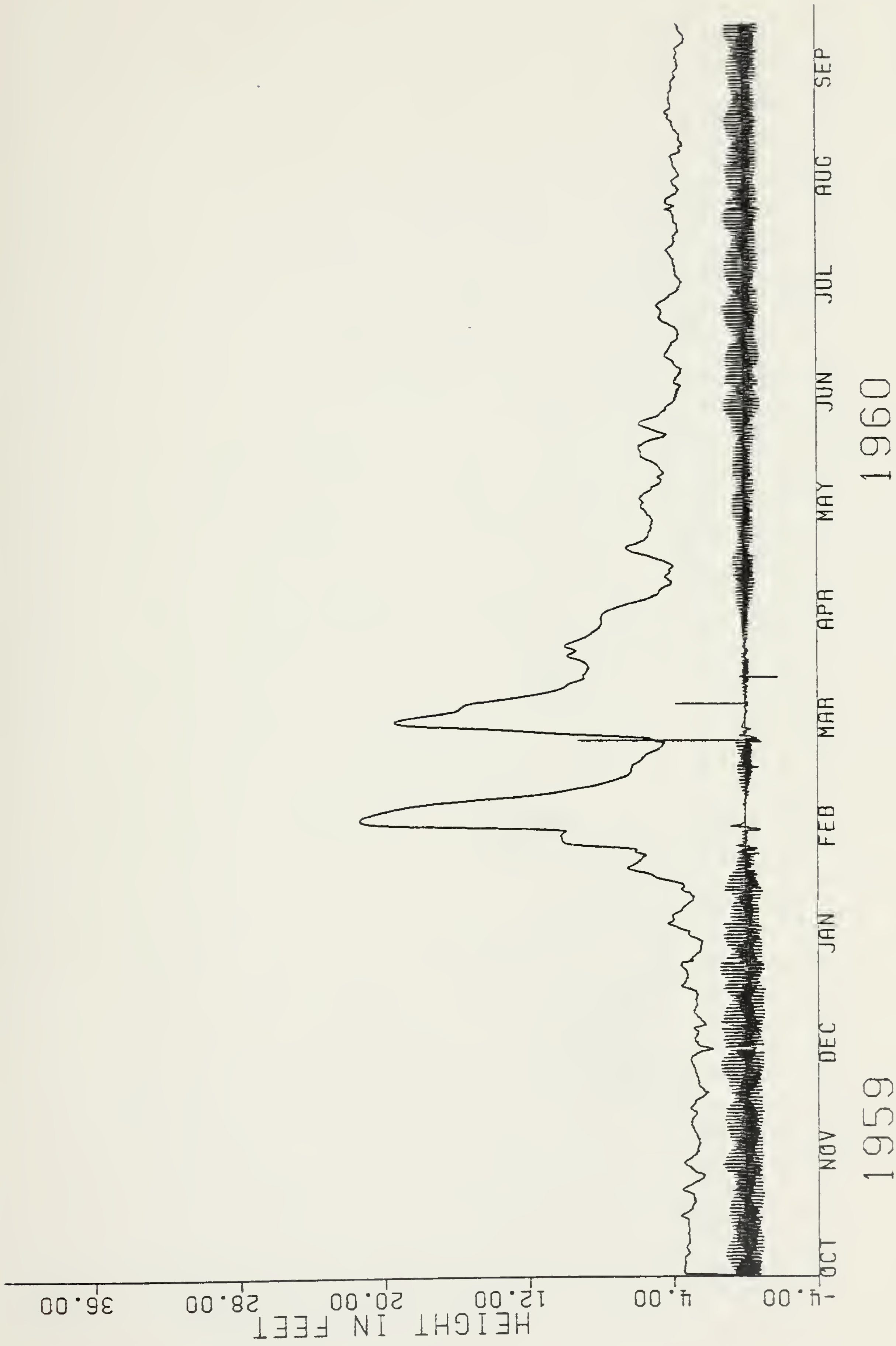
28.00
20.00
12.00
4.00
-4.00
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
1958
1959


HEIGHT IN FEET
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4.00
12.00
20.00
28.00
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OCT
NOV
DEC
JAN
FEB
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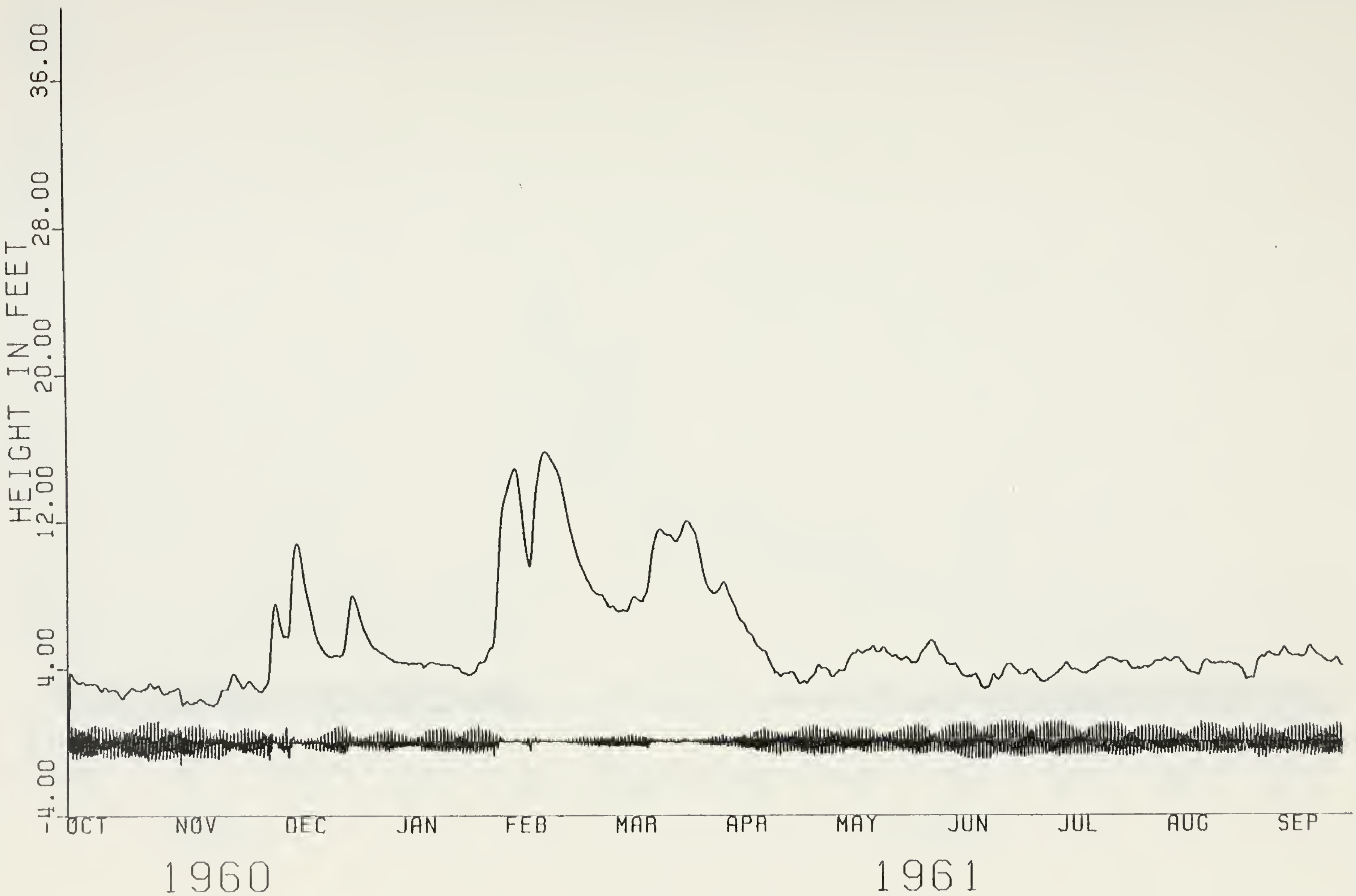
AUG
SEP
1959
1960


HEIGHT IN FEET
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20.00
12.00
4.00
-4.00
OCT
NOV
DEC
JAN
FEB
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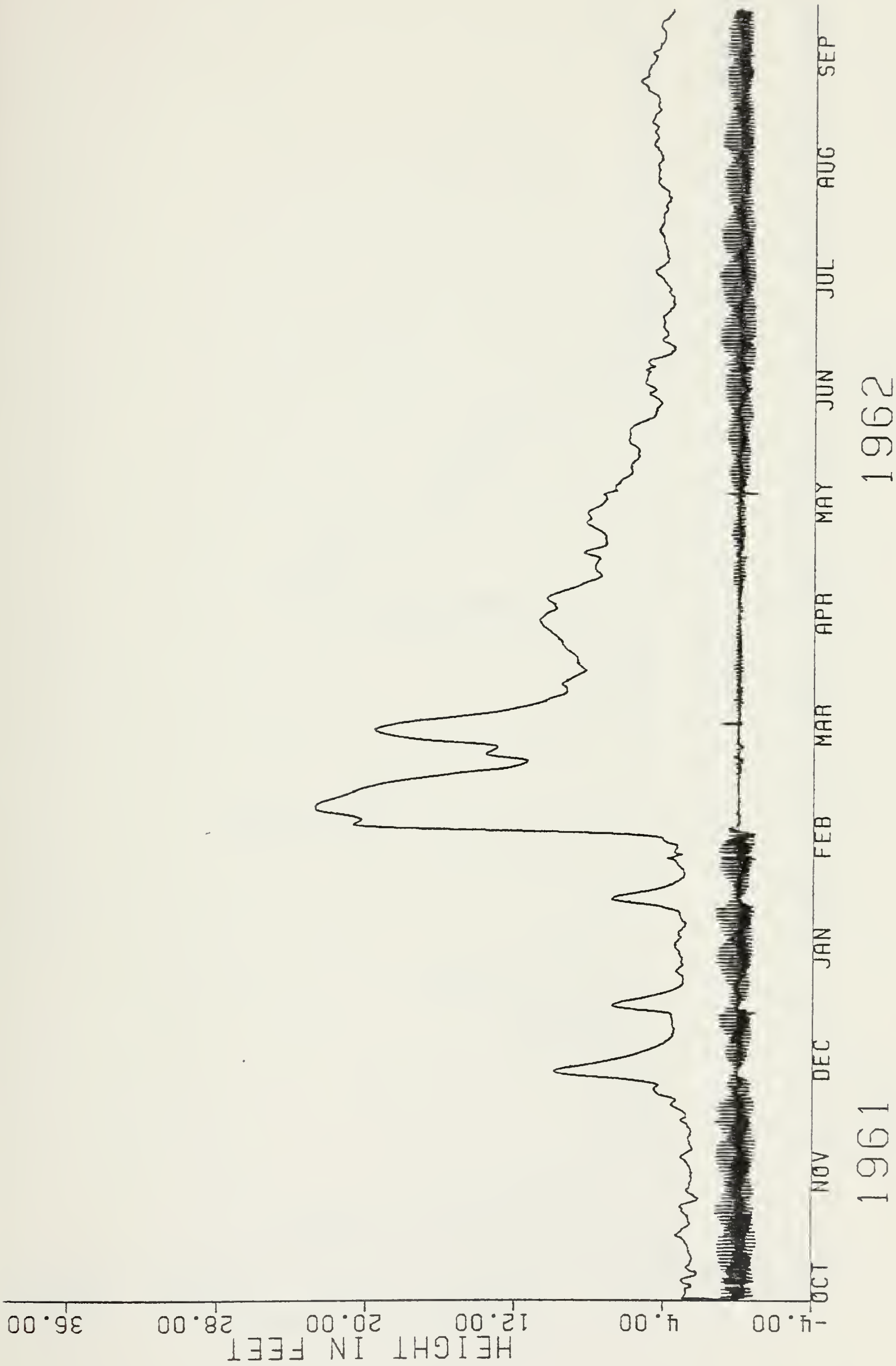
JUN
JUL
AUG
SEP
1960
1961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4.00
12.00
20.00
28.00
36.00
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
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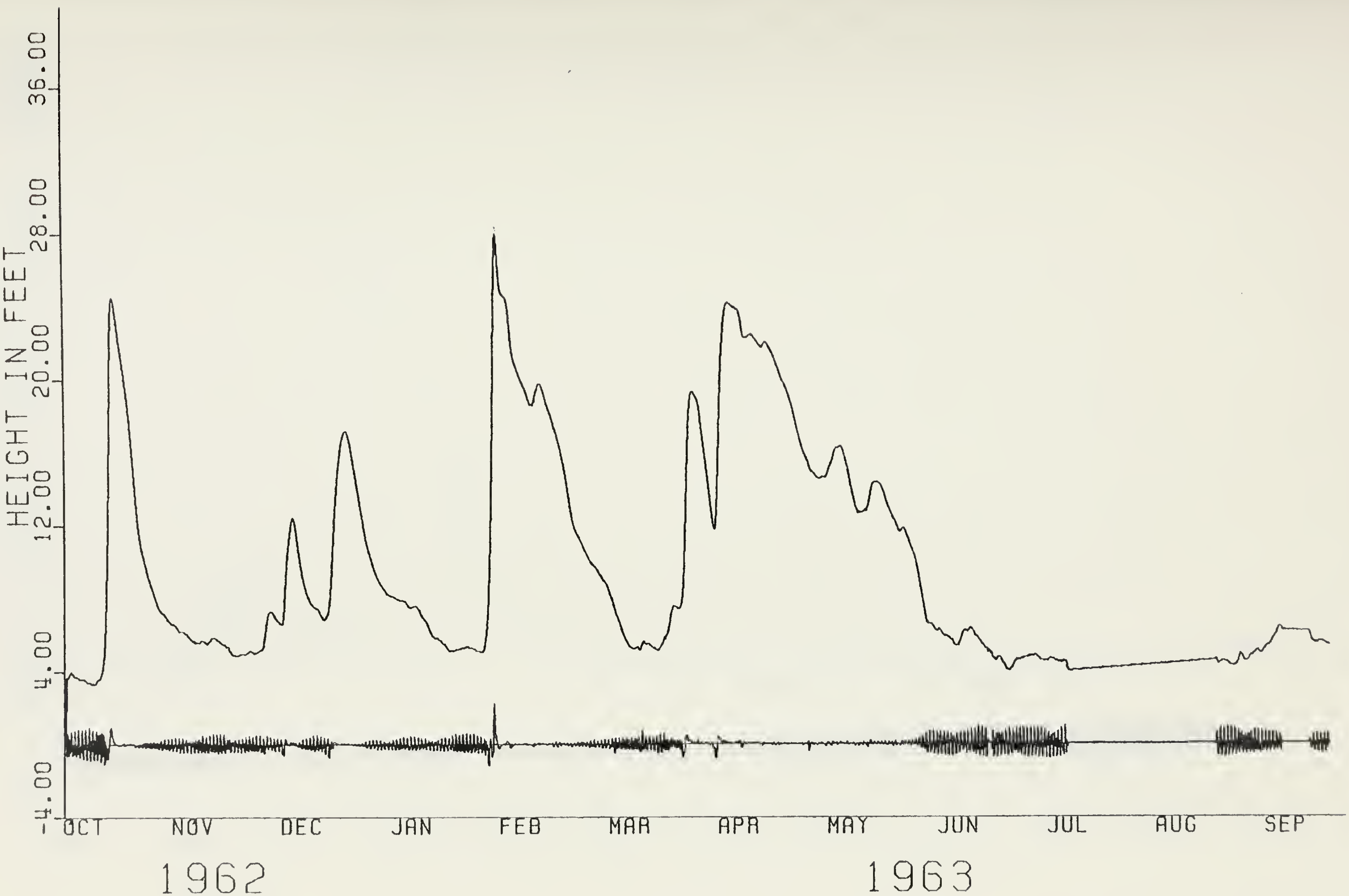
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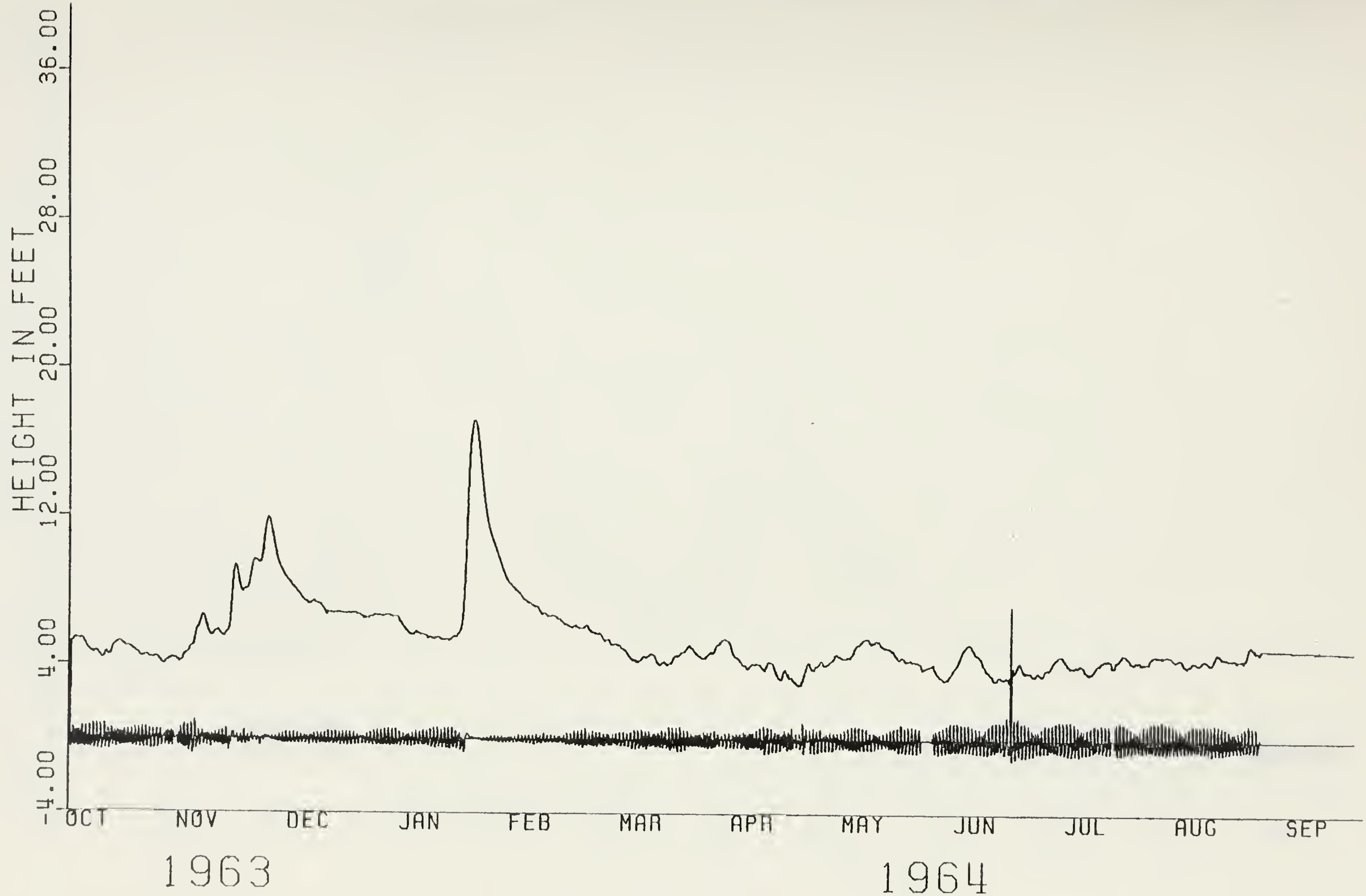
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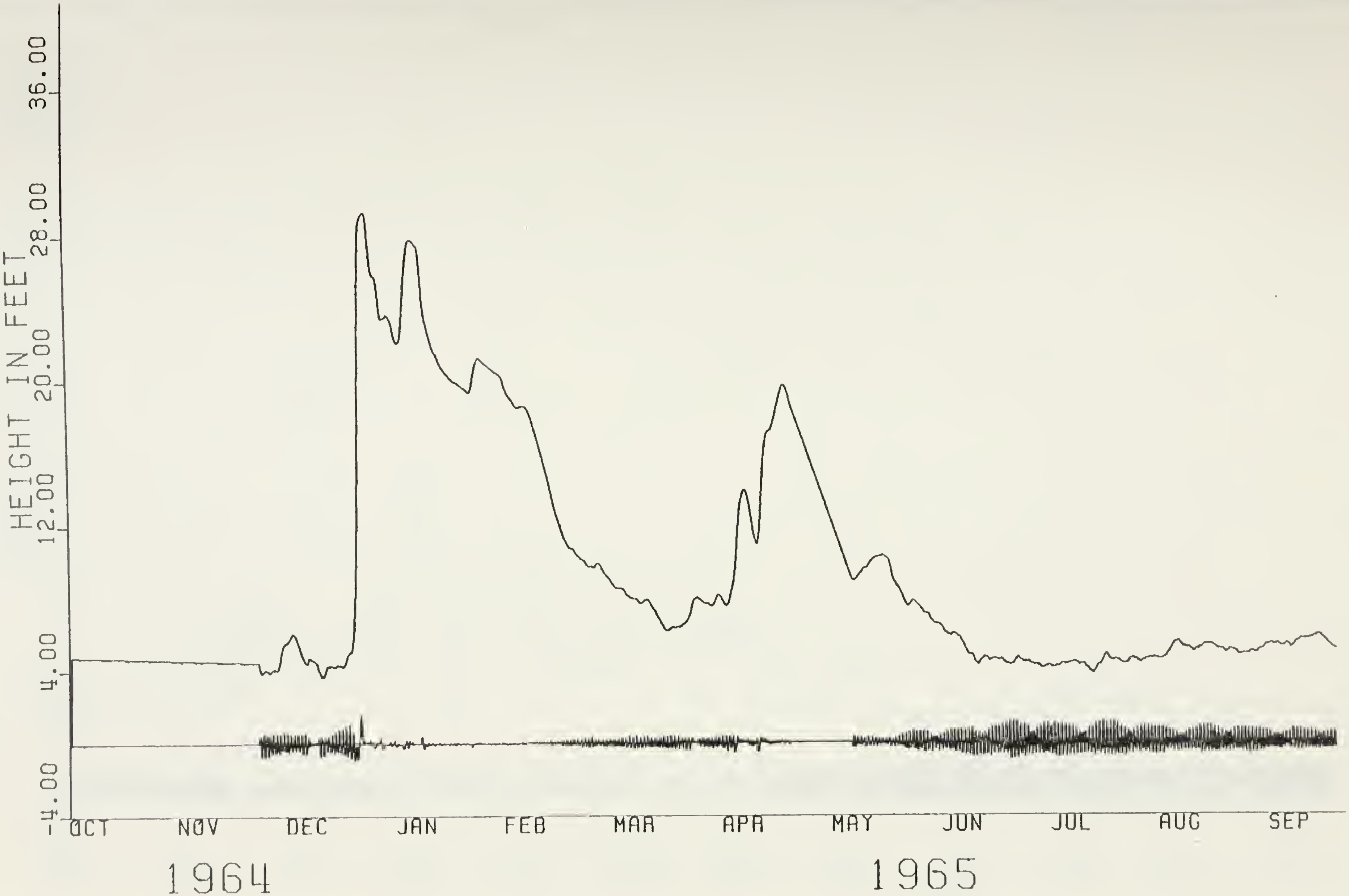
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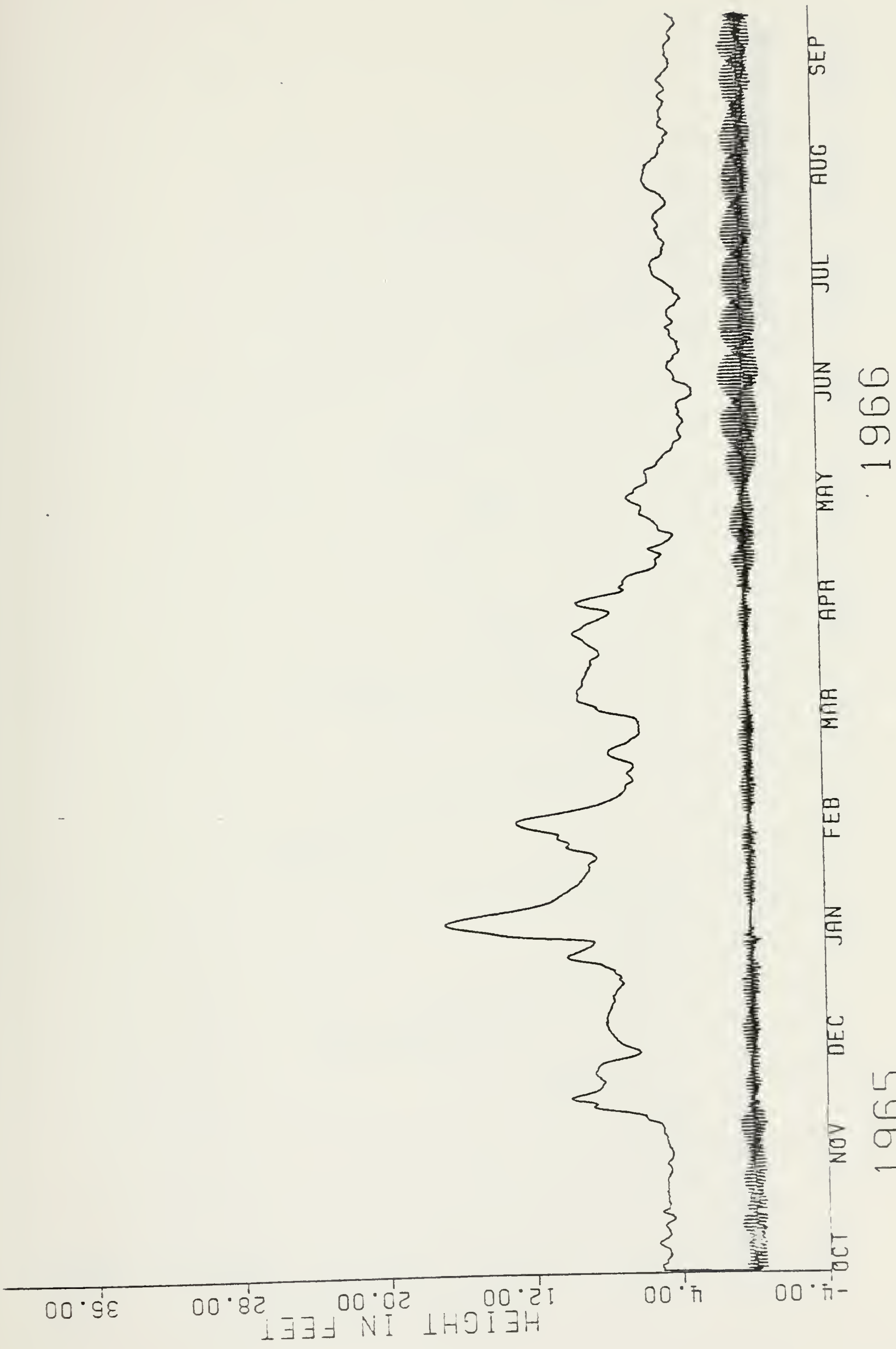
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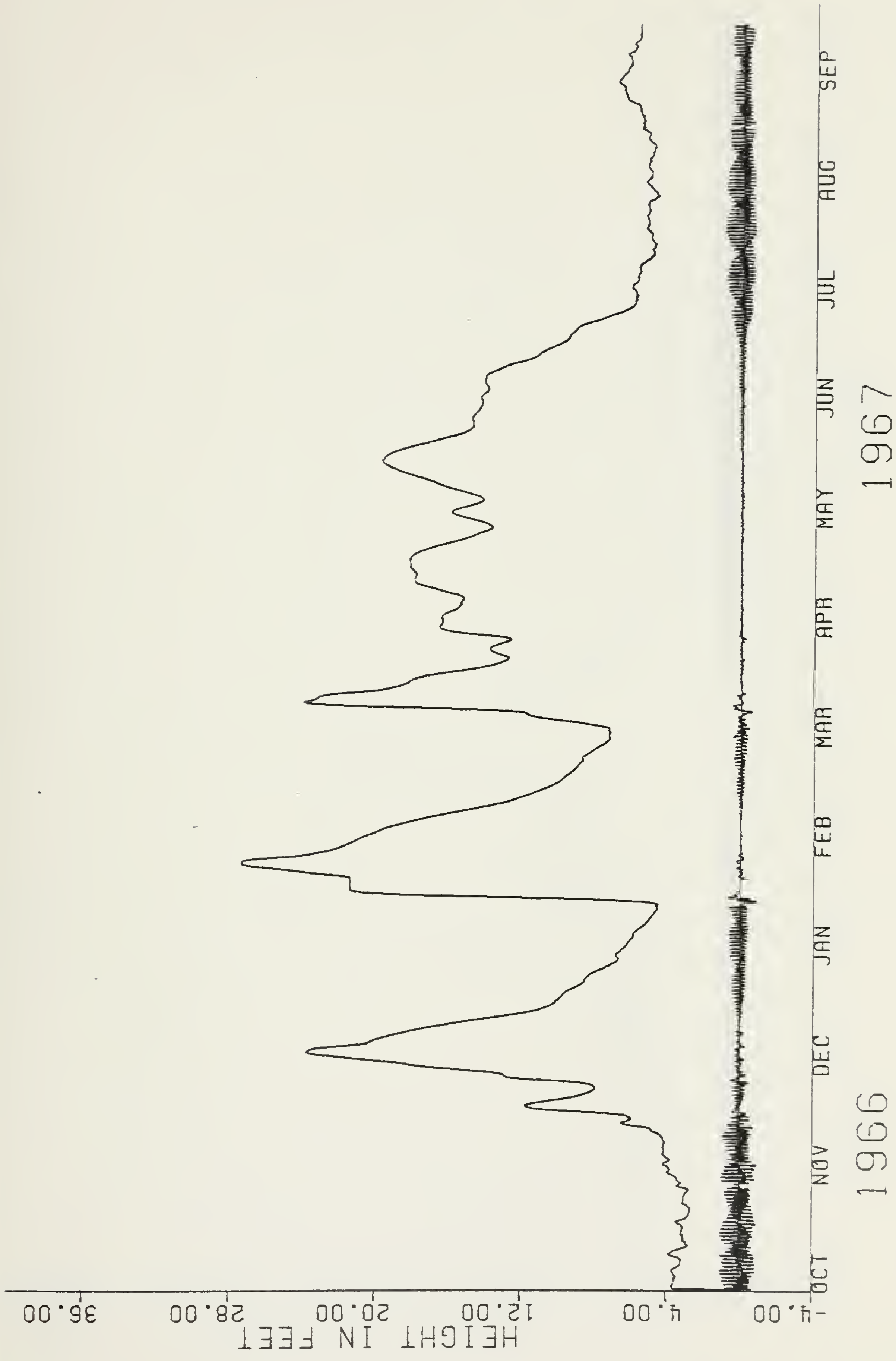
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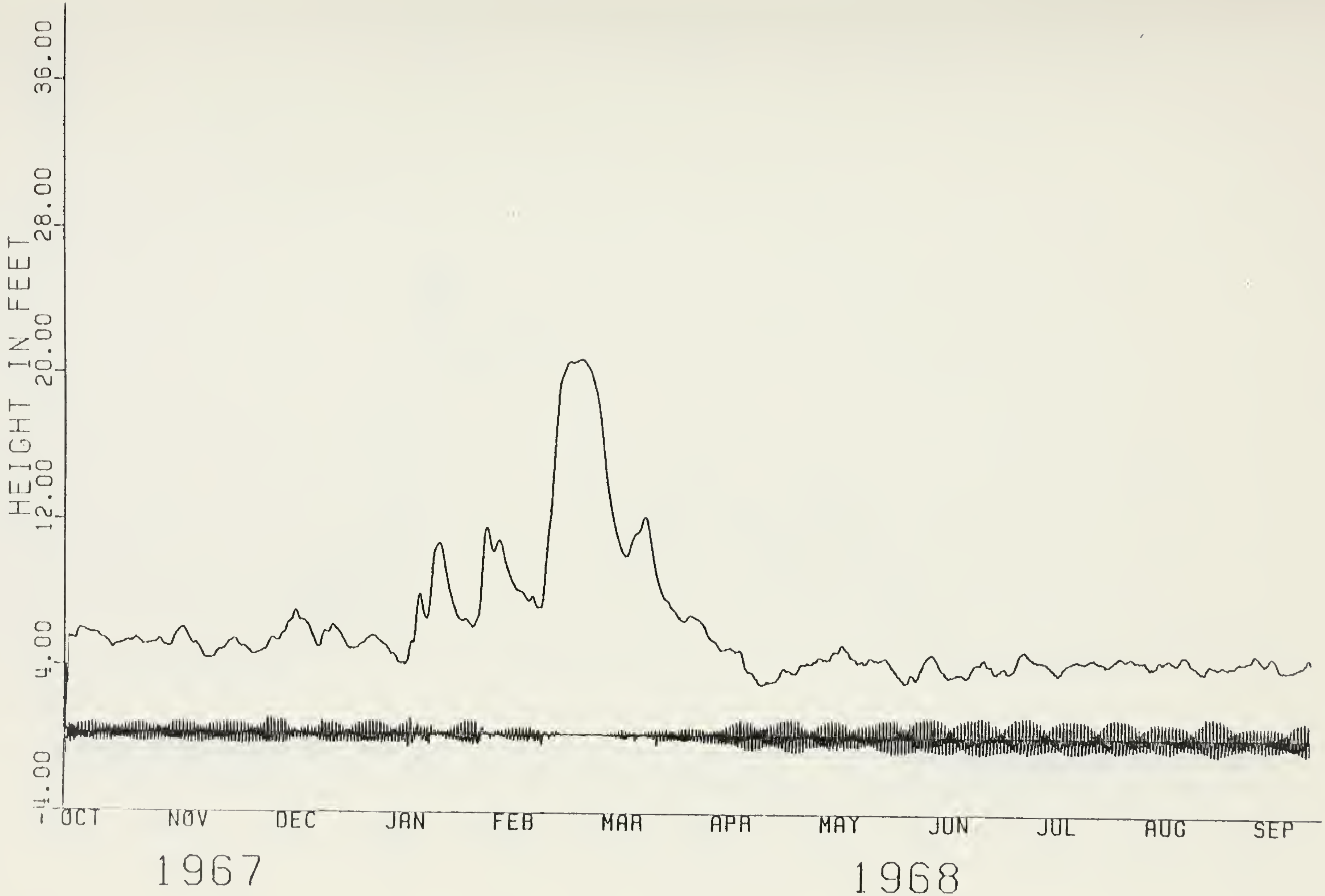
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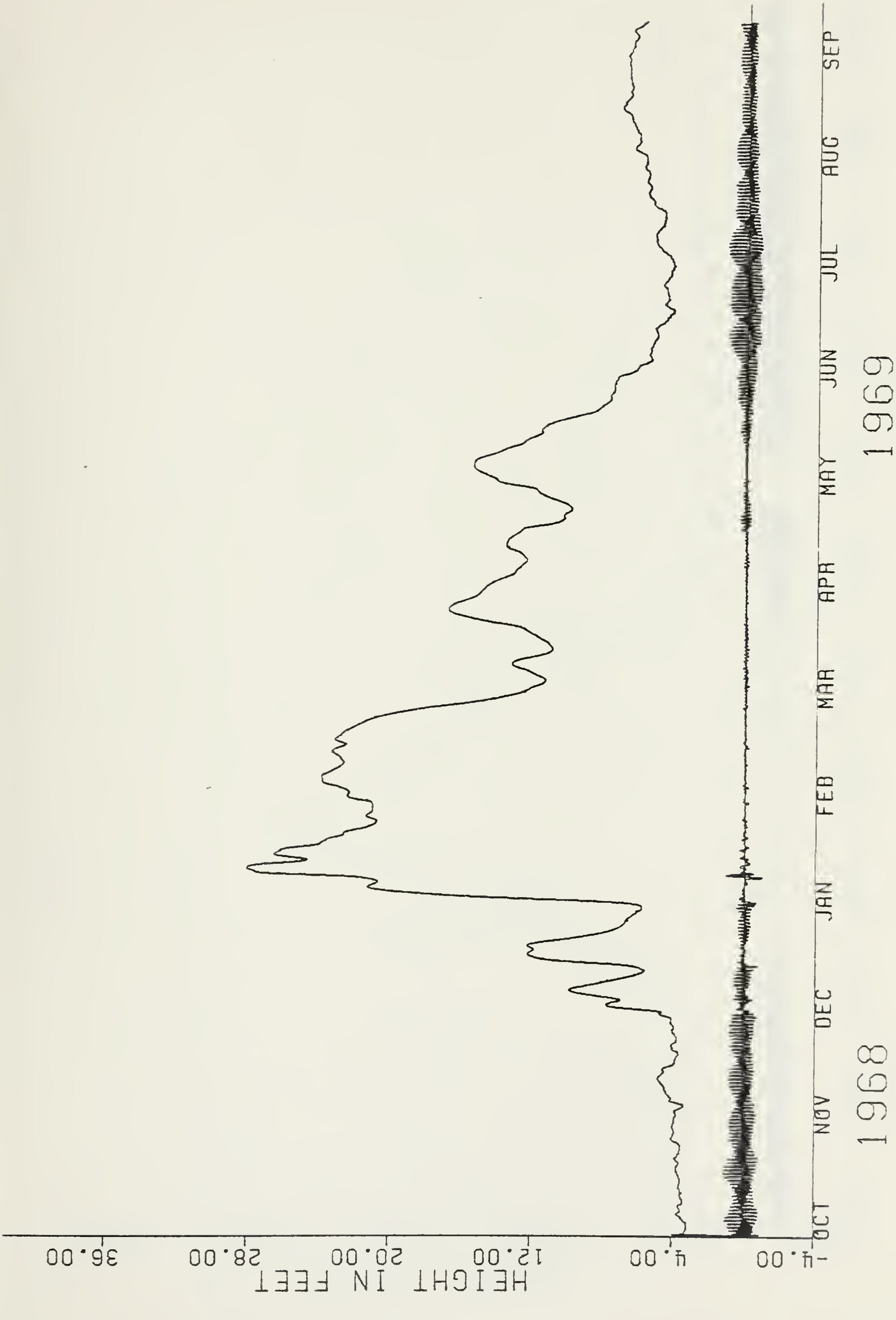
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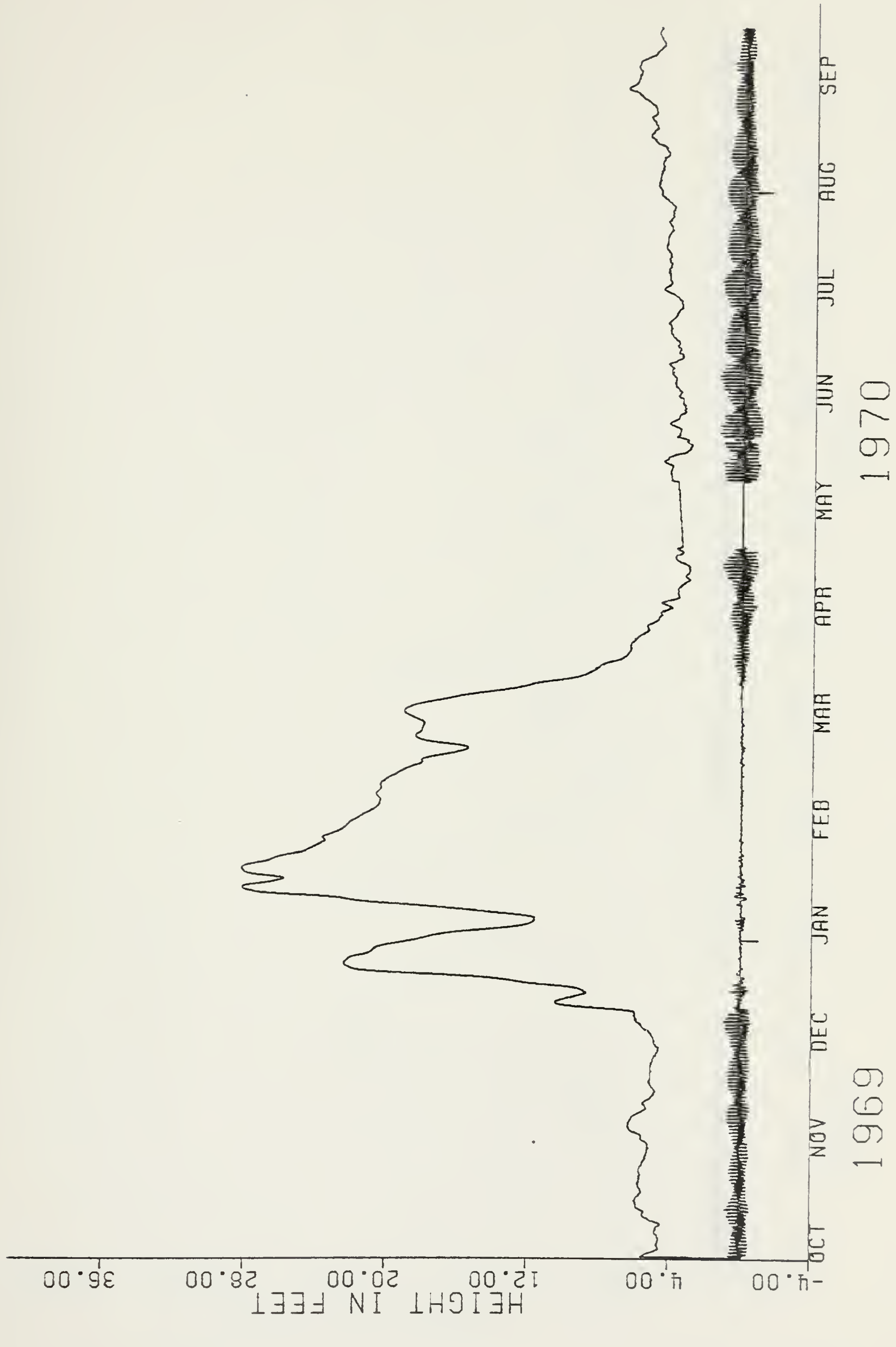
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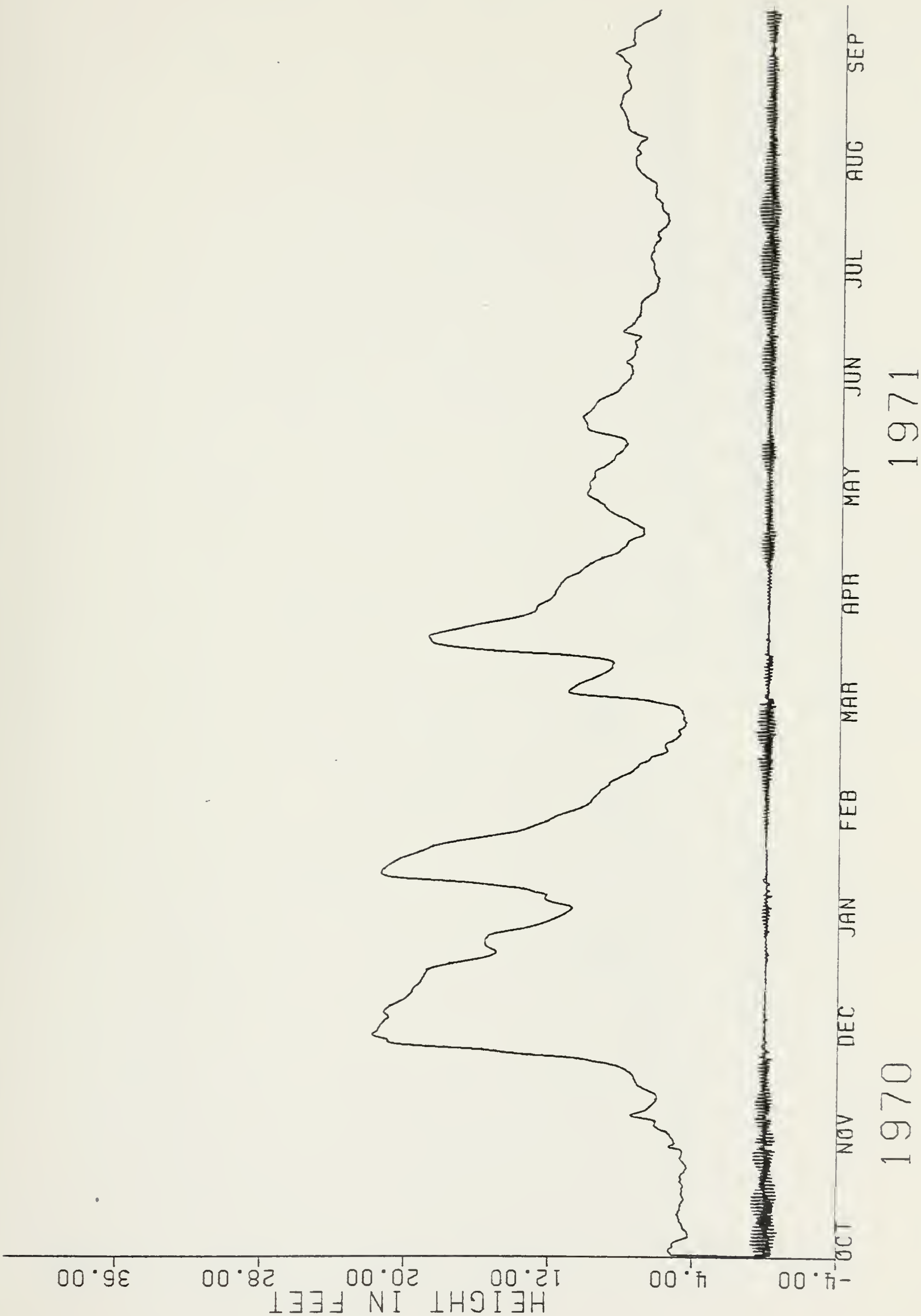
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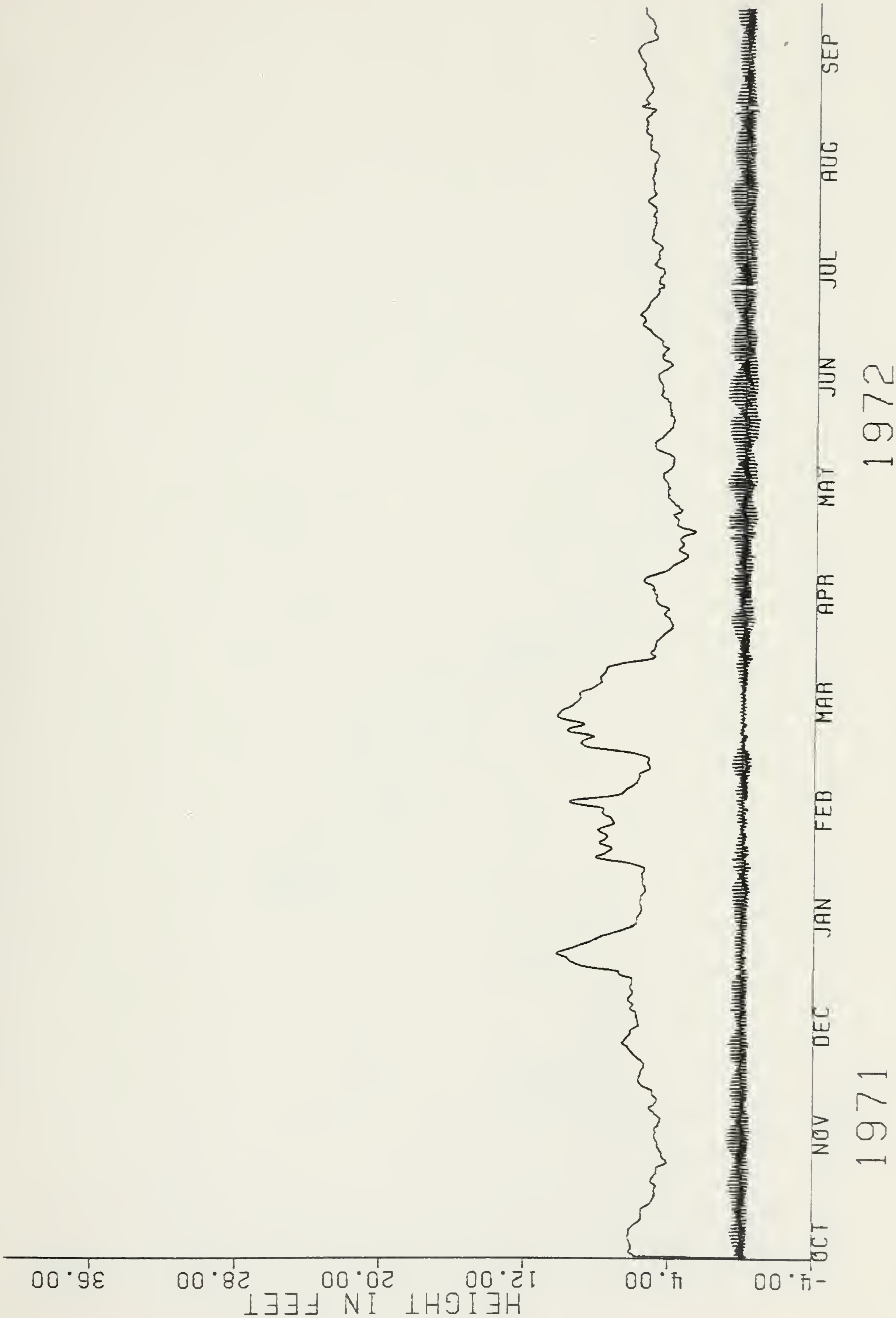
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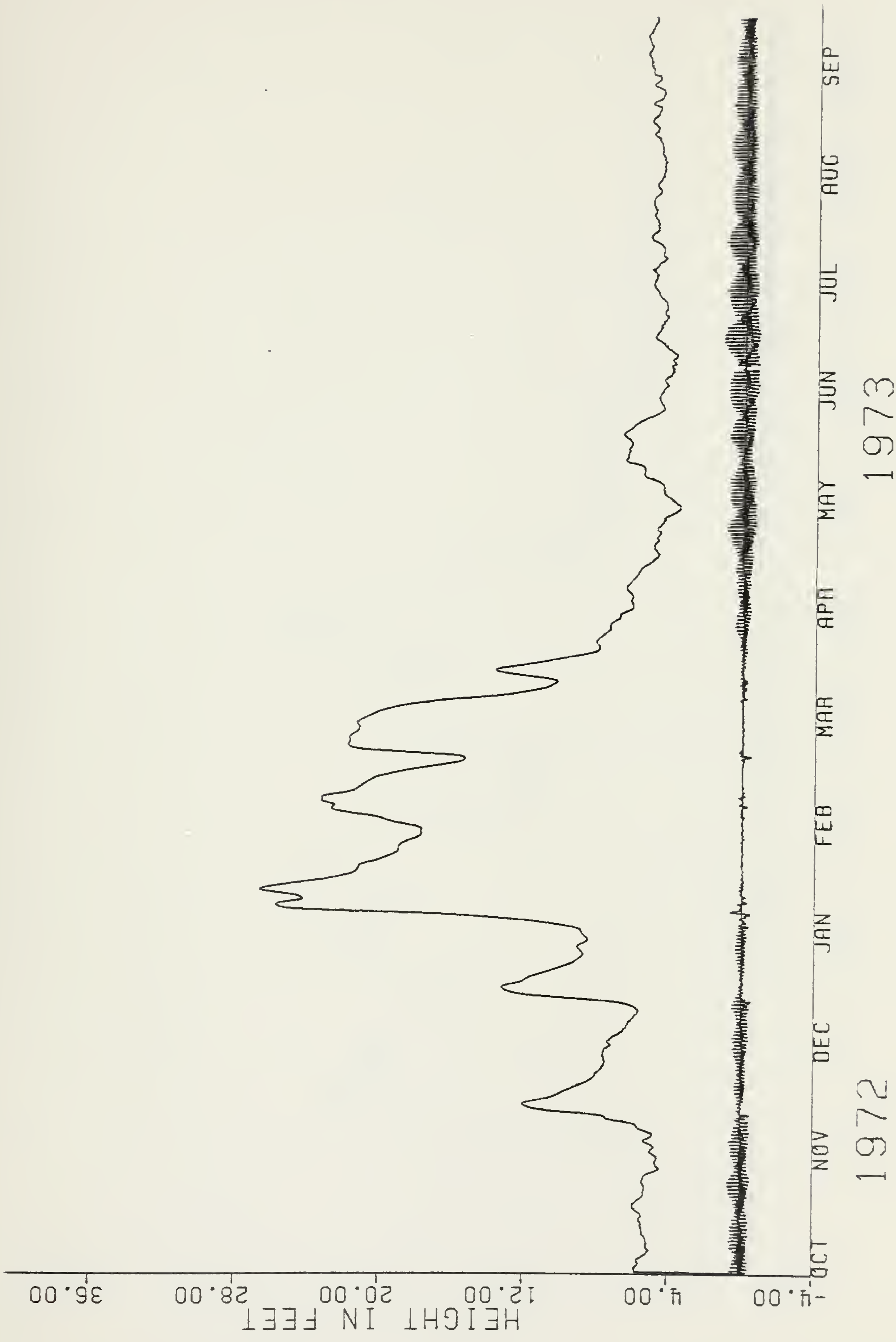
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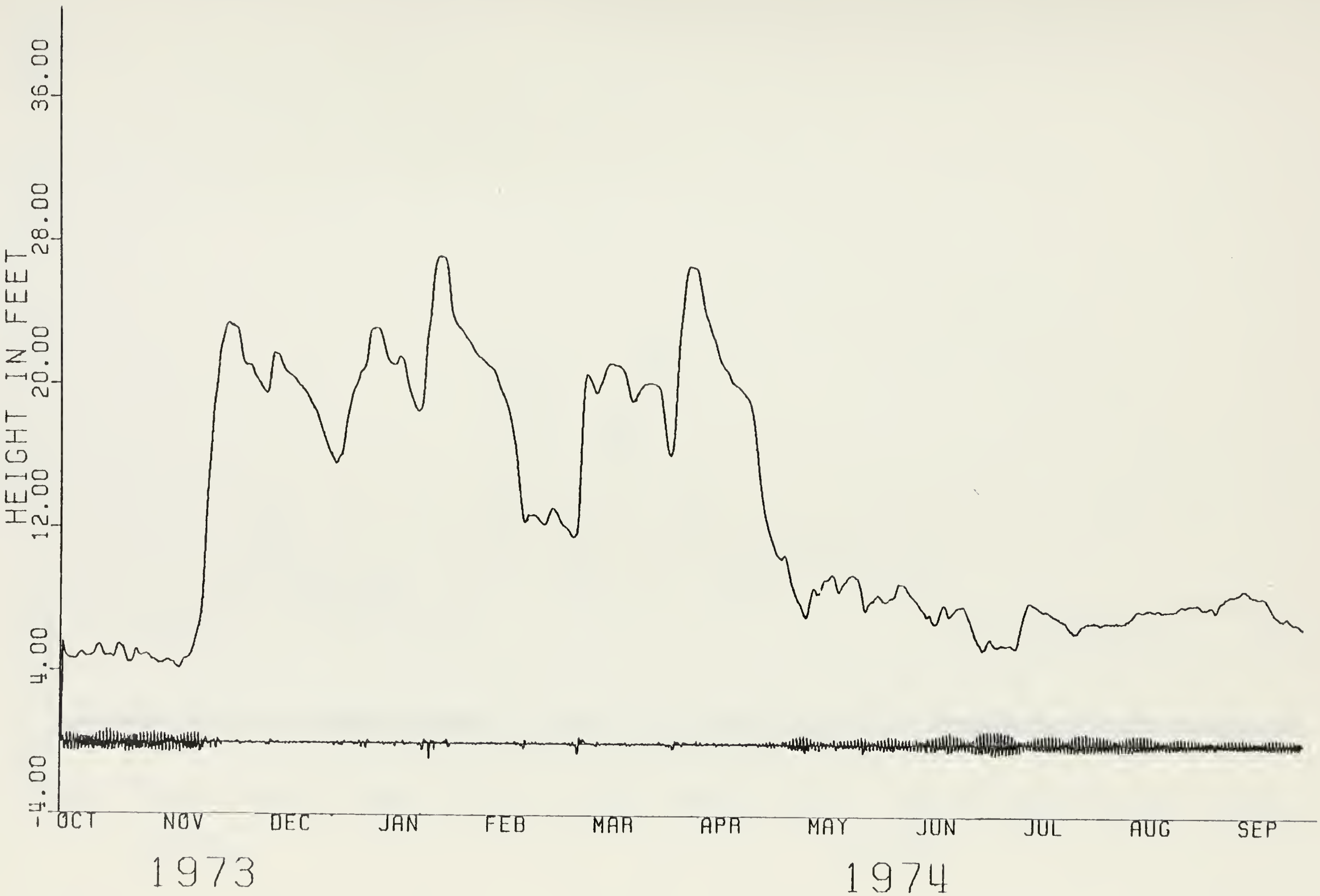

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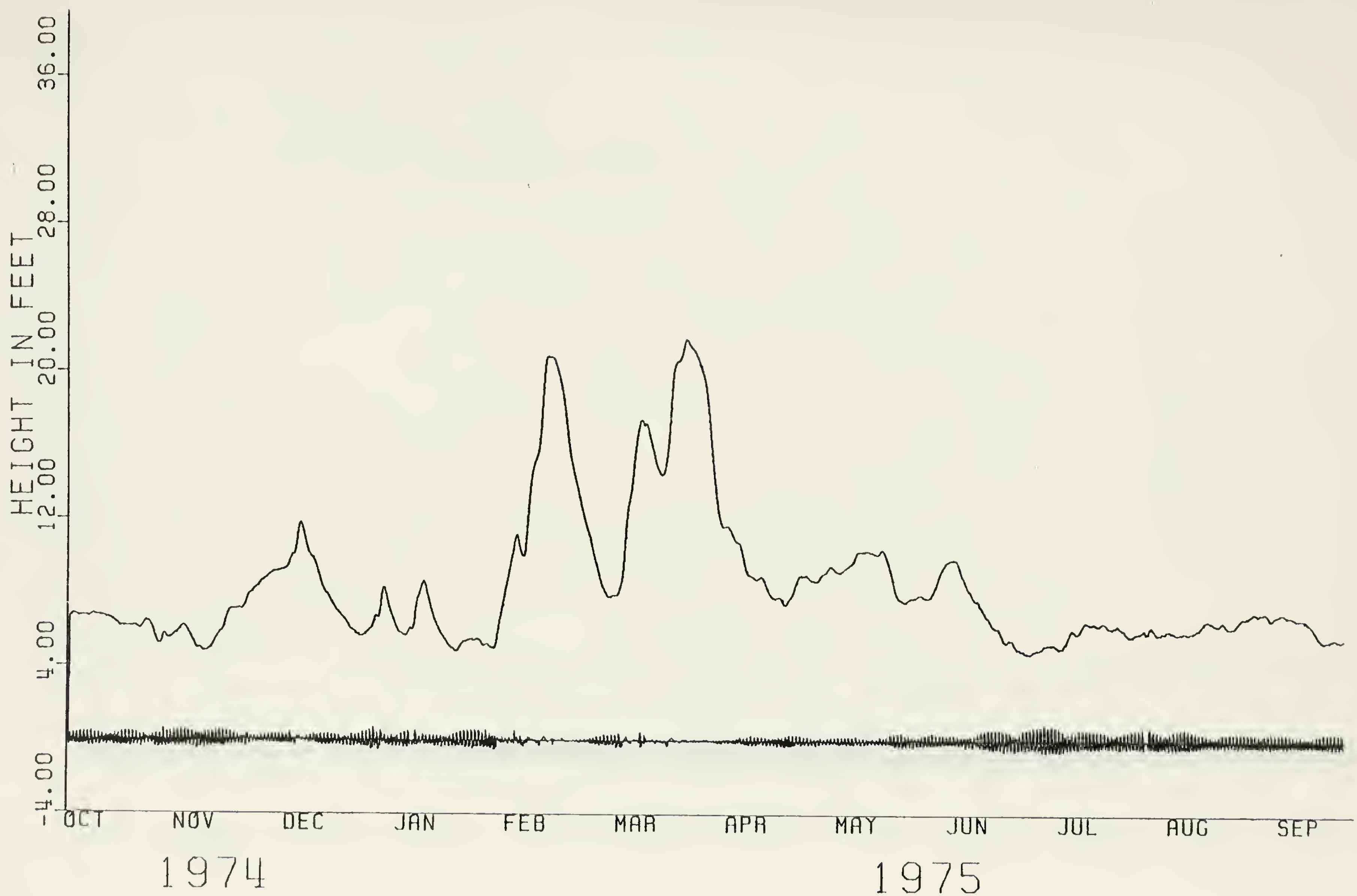

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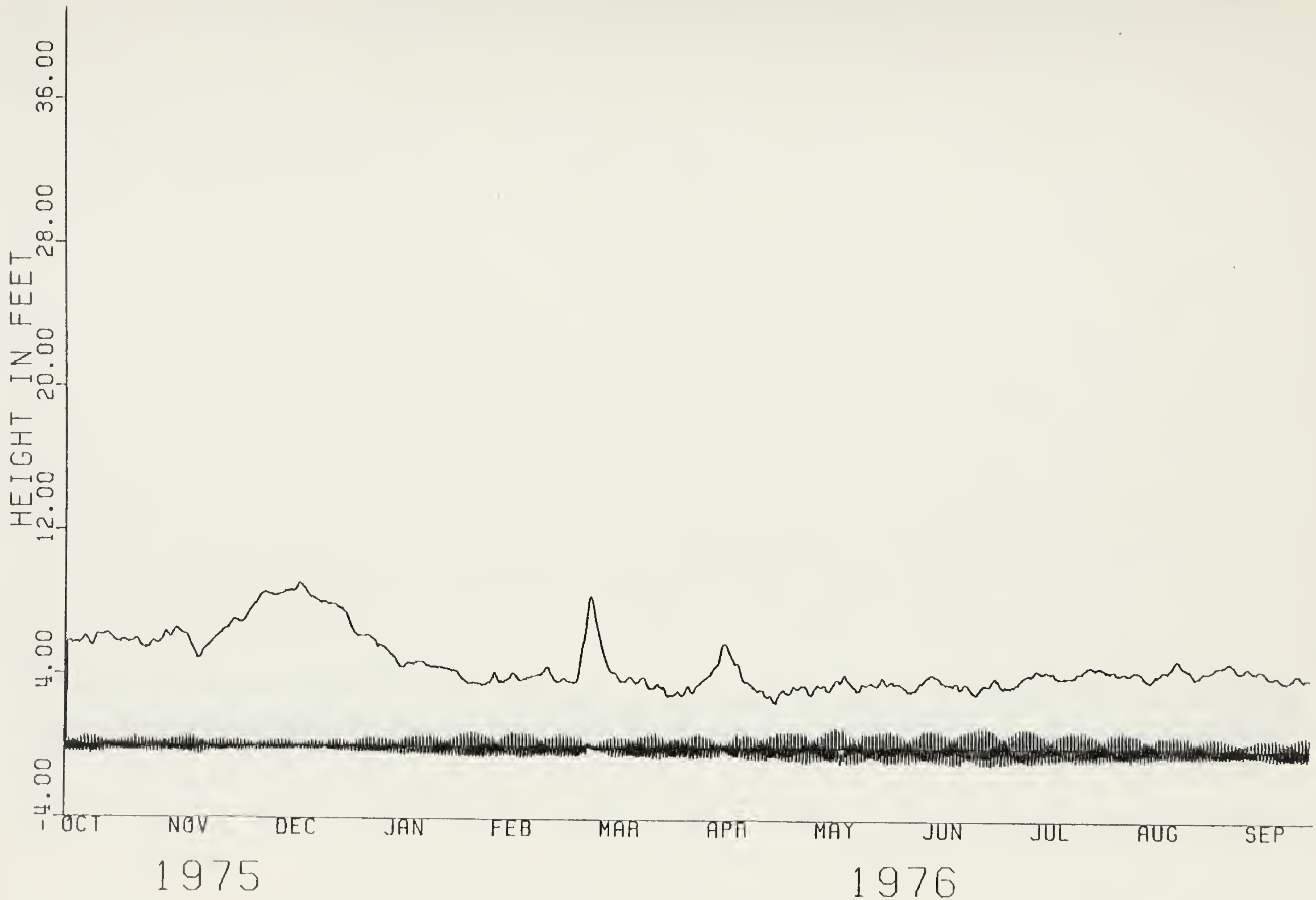
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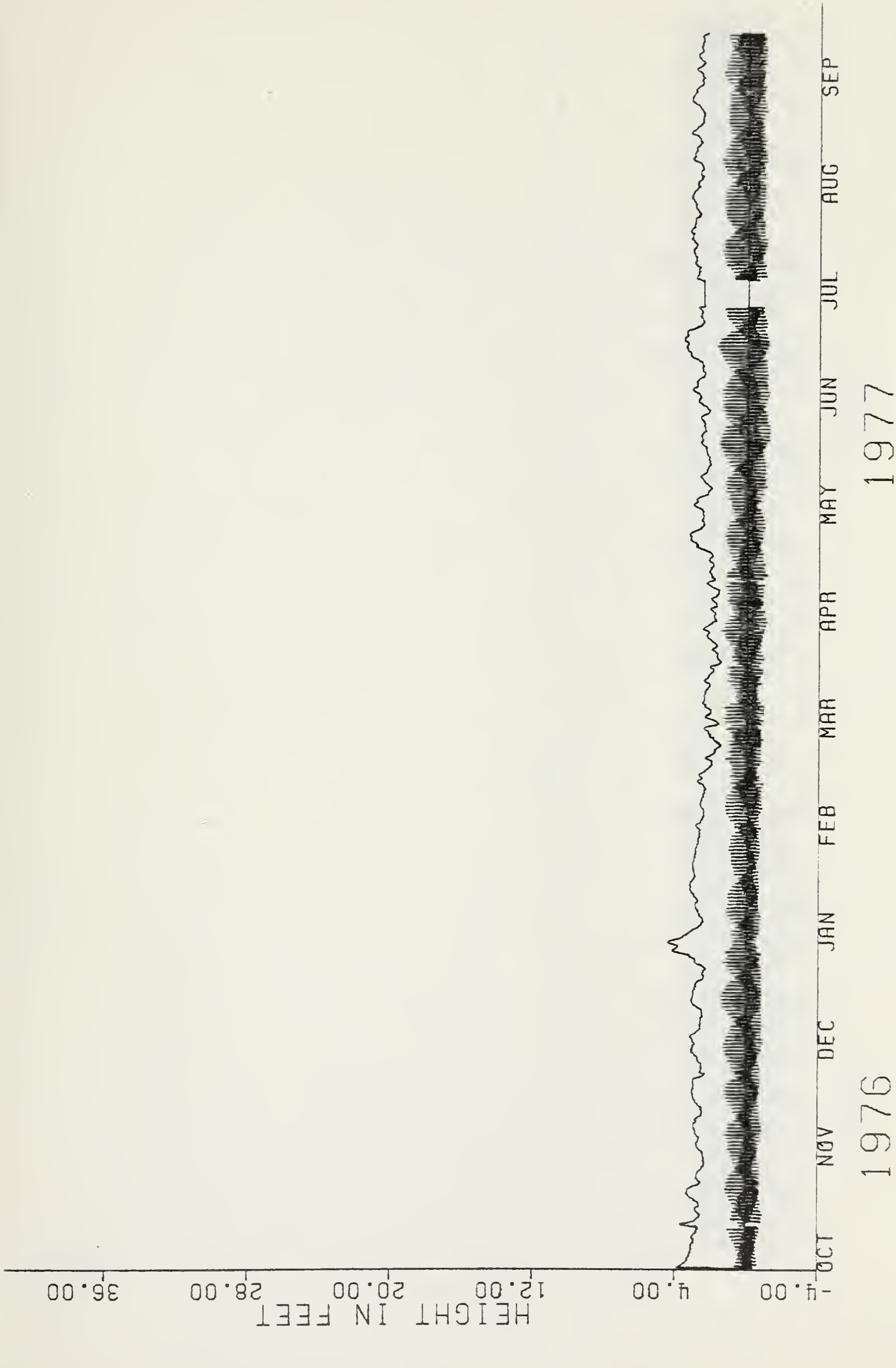
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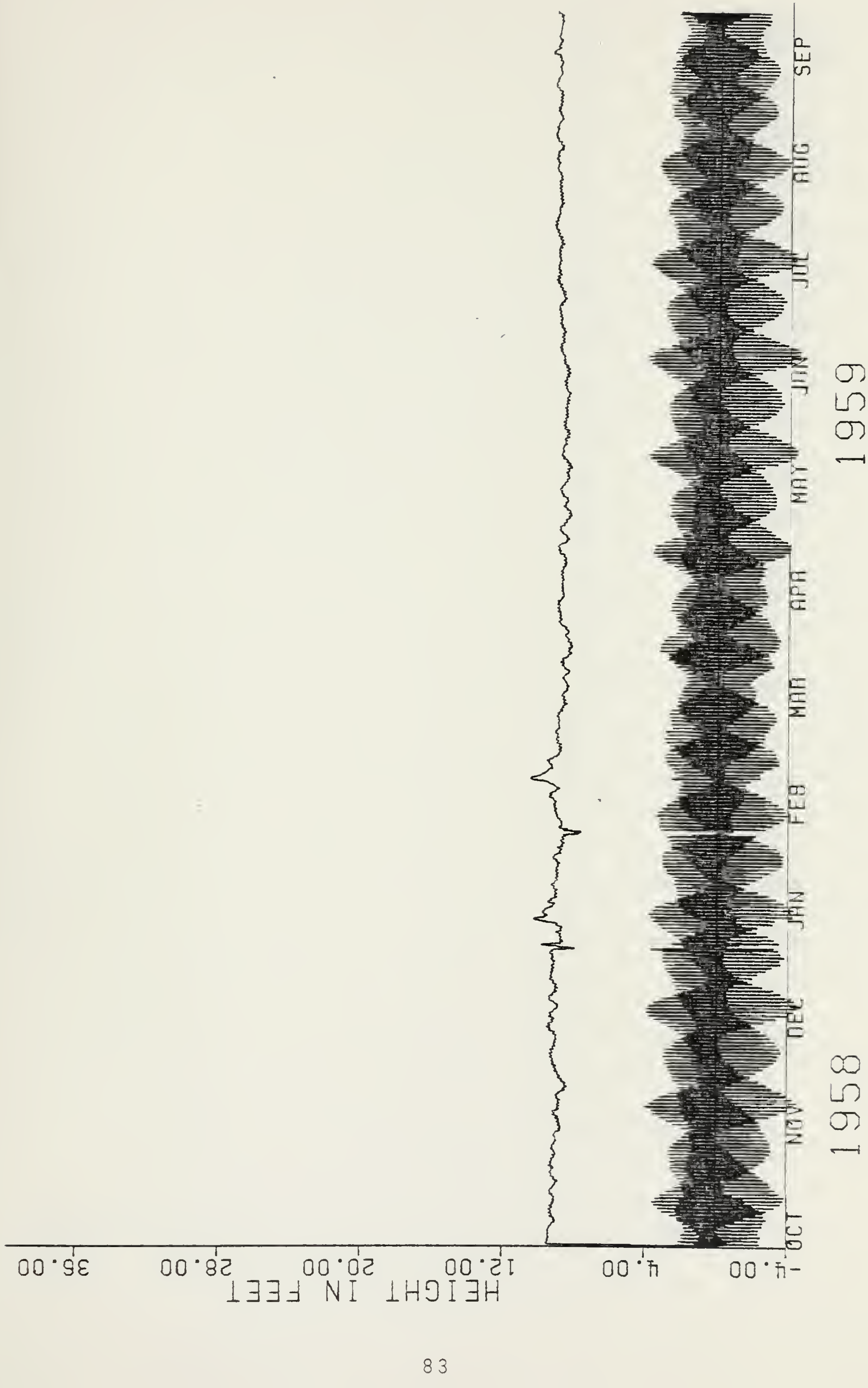
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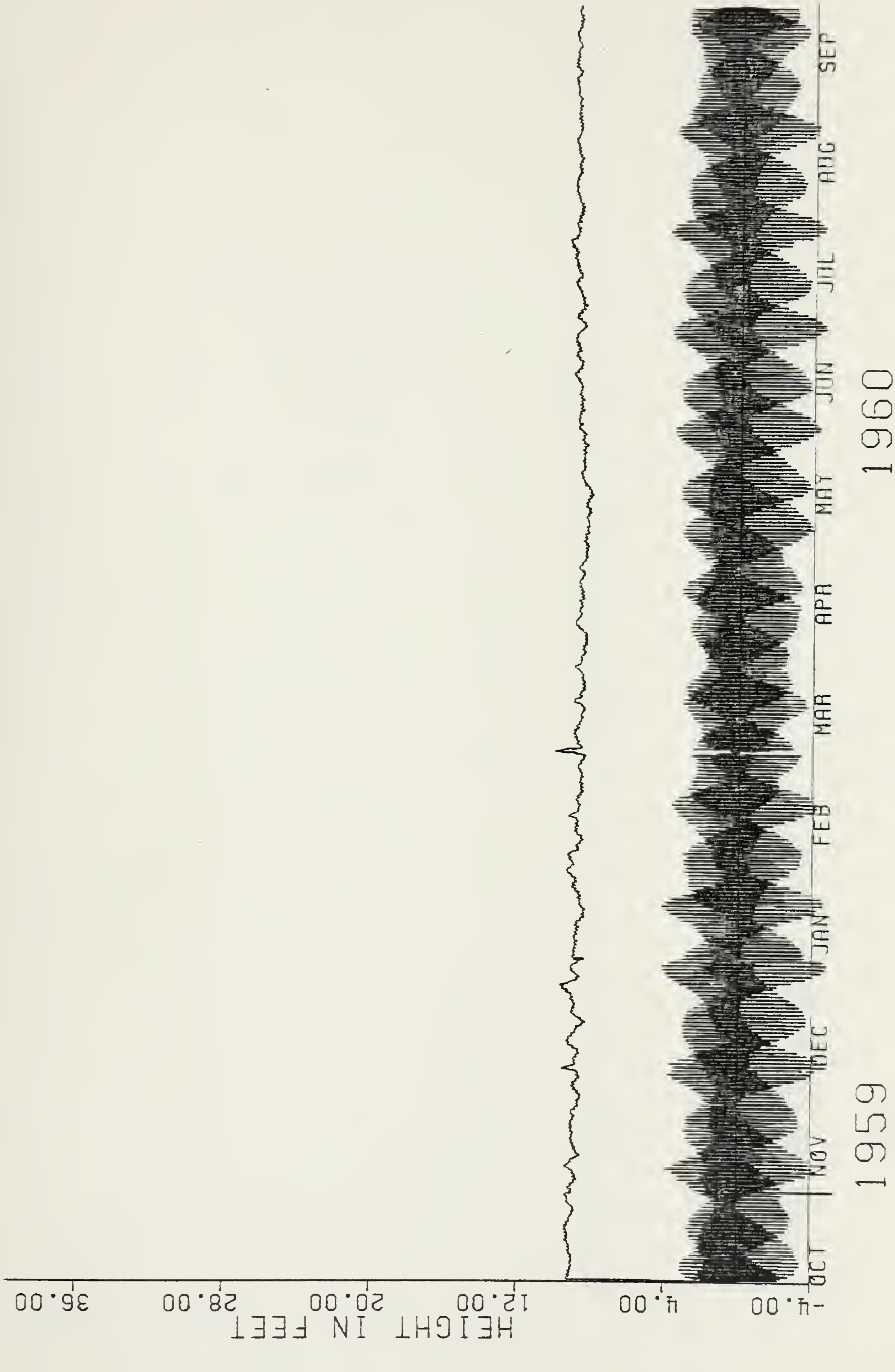
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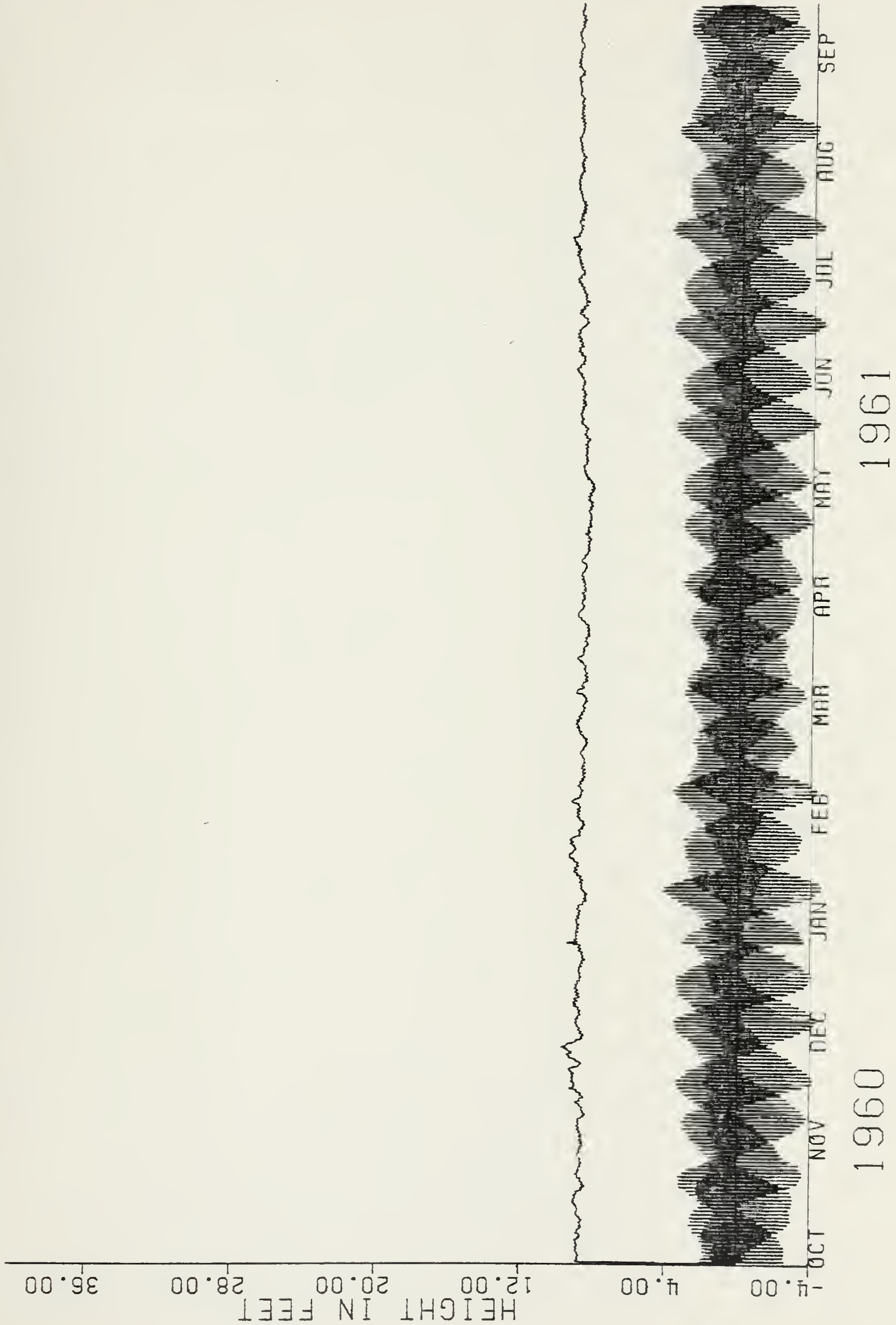
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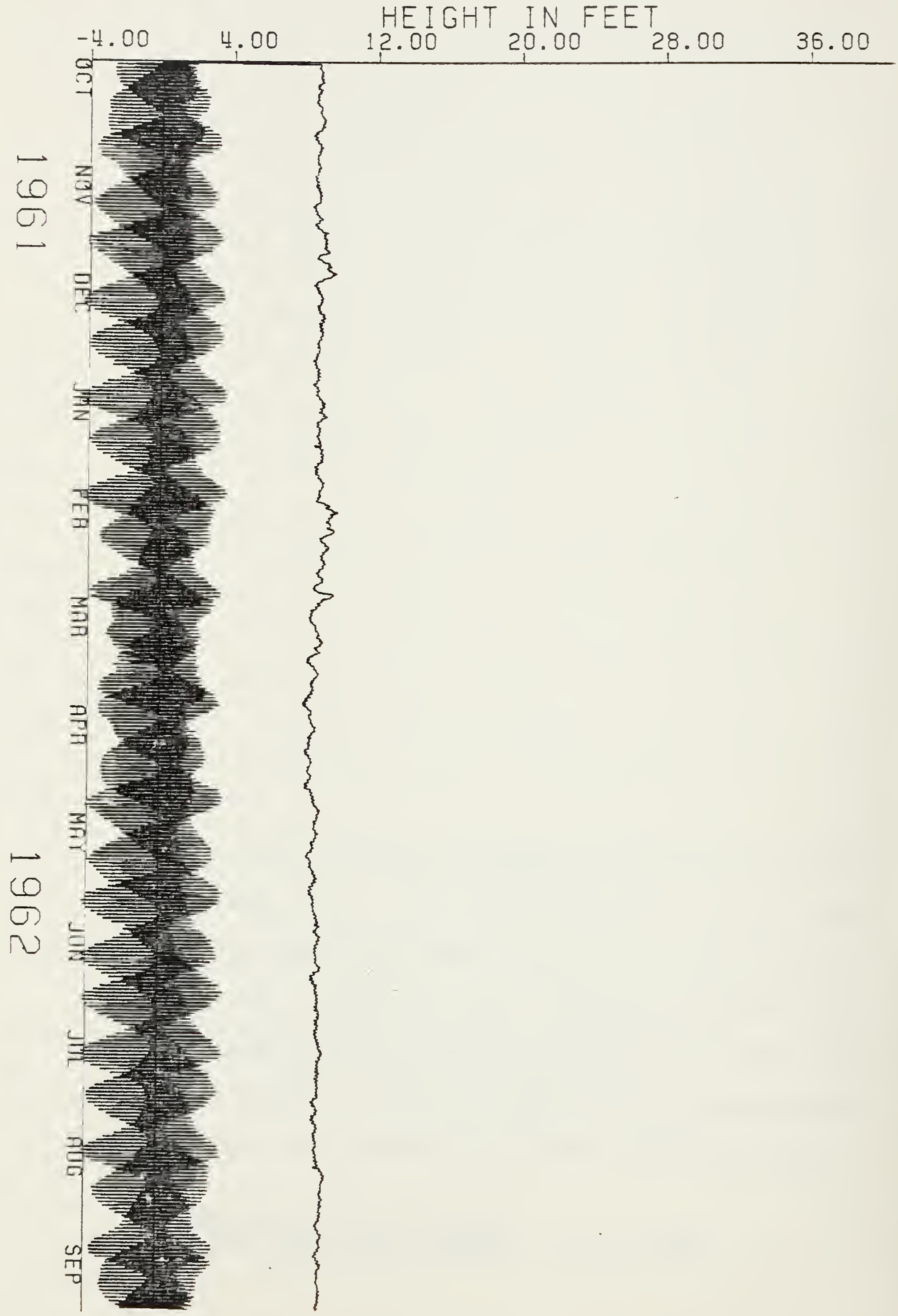
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Appendix C: MONTHLY AND YEARLY MEAN WATER-LEVELS AT SACRAMENTO

This Appendix contains the monthly and yearly mean water-levels for Sacramento derived from hourly heights. Given are both the mean of the raw data and the mean of the non-tidal component. The closeness of the values provides the rationale for computing river datum planes using either raw or residual data. The value in parenthesis indicates an incomplete month of data.

	1958		1959		1960		1961		1962		1963	
	Raw	Residual	Raw	Residual	Raw	Residual	Raw	Residual	Raw	Residual	Raw	Residual
Jan	(11.61)	(11.88)	9.26	9.26	3.85	3.85	4.33	4.34	3.62	3.62	6.52	6.54
Feb	23.65	23.77	13.38	13.37	12.85	12.85	12.44	12.43	14.20	14.19	18.20	18.18
Mar	19.78	19.77	8.95	8.93	10.90	10.90	9.38	9.37	12.42	12.42	8.10	8.09
Apr	22.63	22.61	4.83	4.82	6.47	6.47	5.70	5.69	9.22	9.21	20.09	20.08
May	18.01	17.98	3.96	3.96	5.34	5.34	4.43	4.42	6.82	6.82	14.11	14.10
Jun	11.50	11.47	3.23	3.22	4.25	4.24	4.05	4.04	4.75	4.74	6.27	6.25
Jul	5.24	5.21	3.94	3.94	4.02	4.01	3.93	3.92	4.07	4.06	4.41	4.39
Aug	5.18	5.15	4.43	4.42	3.79	3.78	4.18	4.17	4.37	4.36	4.45	4.43
Sep	5.56	5.52	4.03	4.02	3.81	3.80	4.50	4.48	4.57	4.55	5.53	5.51
Oct	4.60	4.57	3.15	3.14	2.99	2.98	3.20	3.19	9.68	9.67	4.69	4.67
Nov	4.54	4.51	2.79	2.78	3.12	3.11	2.96	2.95	5.68	5.67	7.50	7.48
Dec	4.51	4.47	2.87	2.86	6.33	6.32	5.05	5.04	10.65	10.63	7.08	7.06
Annual	11.32	11.29	5.35	5.35	5.50	5.51	5.26	5.29	7.46	7.45	8.82	8.80

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